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UNITED TECHNOLOGIES HAMILTON STANDARD

DEPLOYABLE ACOUSTIC PROJECTOR SYSTEM (DAPS)
ENERGY SOURCE STUDY
FINAL REPORT

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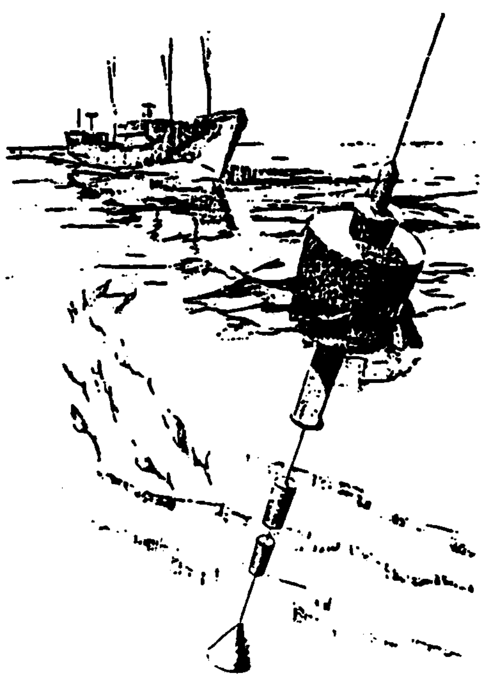

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Results of a study of potential fuel cell sources which may power the Deployable Acoustic Projector System (DAPS) are presented. Several SPE hydrogen/oxygen fuel cell configurations are investigated along with various reactant storage options. The three membranes studied are Nafion 120, Nafion 117, and Dow. Reactant storage options include gas storage tankage, cryogenic flasks, metal hydrides and chemical storage. Reactant storage options at 3000 psi and 6000 psi are discussed. Conversion of the SPE fuel cell to ac or use of an inverter are also discussed. Also presented is system safety and reliability information along with weight, volume, and cost trade-offs for the various hardware configurations.

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EXECUTIVE SUMMARY

This report presents the results of a study conducted by Hamilton Standard for the investigation of potential fuel cell energy sources which may power the Deployable Acoustic Projector System (DAPS). Several SPE hydrogen/oxygen fuel cell configurations are investigated along with various reactant storage options. Also presented is system safety and reliability information along with weight, volume and cost trade-offs for the various hardware configurations.

Fuel cell power systems considered include both existing SPE cell hardware designs as well as hardware which could be developed and qualified for service within three years time. All designs are based on the solid polymer electrolyte technology, which has been steadily evolving over the past thirty years. The criteria used for power system design suitability include a nominal mission power requirement of 100 kW output for ten-second durations occurring approximately every fifteen minutes. The peak power is anticipated to be an output of 400 kW for two-second durations over approximately the same interval. Use of a high power inverter is investigated for conversion of D.C. output to A.C.

Results of the study indicate that of the three membranes studied; Nafion® 120, Nafion 117 and Dow, all can be utilized to meet the 100 kW and 400 kW power requirements of the DAPS. This assumes that the 100 kW level includes a current of 1000 amperes at 100 volts and the 400 kW power level requires a current of 1000 amperes at 400 volts. In general, high performance membrane materials such as Nafion 117 and the Dow formulation offer significant system weight and volume savings over the Nafion 120 membrane. Fuel cell designs which utilize the Nafion 120 membrane represent a mature technology while those which contain these high performance materials are somewhat less mature. All three membrane options utilize the circular screen type hardware which is presently being utilized for gas generation in nuclear submarines.

Choice of reactant storage means affects system cost, weight, volume and recharge requirements. 3000 psi gas storage in commercially available metal

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tankage offers the lowest cost/technical risk option. 6000 psi gas storage has been implemented in several applications and also represents a low technical risk option. Higher gas storage pressures or composite tankage can increase overall system power density. Metal hydrides used for hydrogen storage can reduce system volume, however, a significant weight and cost penalty must be paid. Cryogenic storage of hydrogen and oxygen represents a low weight/volume storage option; however, this technology is somewhat difficult to implement due to recharge requirements. Chemical storage means have been previously used in smaller buoy systems, but require complete replenishment after the mission, therefore incurring high life cycle costs.

Hamilton Standard has demonstrated in laboratory cells that the SPE fuel cell may be converted to produce alternating current directly, thereby eliminating the need for an inverter. This technology advance could lend itself to reducing system cost/weight/volume. Although the fuel cell normally produces direct current (D.C.), this output may be converted to alternating current (A.C.) through the use of a high power inverter. Many inverters are presently available as off-the-shelf items, however, relatively few can be found in the appropriate power range. Nearly all of these inverters must be adapted for the reduced cooling requirement of the anticipated DAPS duty cycle. Regardless of the design, an inverter will add a significant weight (1500-2000 pounds) and volume (10-15 Ft.^{3}) to the overall system.

1.0 INTRODUCTION

This report presents the results of a study conducted by Hamilton Standard for the investigation of potential fuel cell energy sources to provide the on-board power for the various Deployable Acoustic Projector System (DAPS) components. Components to be powered include a transducer, control/command, buoyancy, signal conditioning and communication. Included in this report is a discussion of the various SPE fuel cell power system options, reactant storage schemes, system requirements, power conditioning equipment, safety features and cost trades applicable to the DAPS concept.

The SPE fuel cell is uniquely suited as an energy source for the Deployable Acoustic Projector System. This energy source consumes gaseous hydrogen and

oxygen reactants to produce electrical energy. This direct conversion of chemical energy to electrical energy represents a highly efficient process. Safety hazards are minimized in the SPE hydrogen/oxygen fuel cell since positive separation of reactants is always maintained. Our systems safety tolerate all failure modes due to a well established pressure hierarchy and system operating philosophy as detailed in Section 11 of this report.

The solid polymer electrolyte fuel cell has demonstrated a superior power density that makes it highly desirable for the DAPS, which must operate underwater at high power levels. The selection of the optimum fuel cell power supply involves several key considerations. These include the type of electrolytic membrane used, the operating current and the fuel storage method. Several different membranes can be used, each with a different characteristic polarization curve (relationship between current density, in $Amps/Ft.^2$ and cell voltage). The cell voltage determines not only the terminal voltage and output power, but also the fuel efficiency. The actual current density will influence the size of the cell stack and the fuel efficiency. The fuel storage method and fuel efficiency affects the size and weight of the fuel load and, hence the total plant size.

2.0 TECHNOLOGY OVERVIEW

The development of the solid polymer electrolyte technology and related products has been a continuing effort since the 1950's. SPE fuel cells were first developed as a viable product around 1960. Over the past thirty years, improvements in membrane and electrode technology allowed for significant performance enhancement in SPE fuel cells and also promoted a broader technology base. Proven applications include:

- Water electrolysis - production of hydrogen and oxygen for space, undersea and commercial/industrial applications.
- Oxygen concentrators - conversion of air to 99.5% oxygen for aircraft life support.
- Primary hydrogen/oxygen fuel cells - electrical power generation for space, sea and ground power.

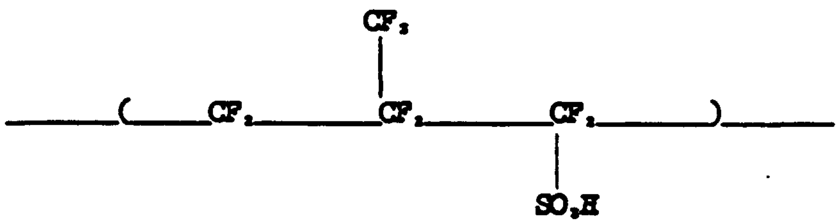
- Regenerative hydrogen/oxygen fuel cells - energy storage for aerospace applications.

The solid polymer electrolyte and catalytic electrode technologies serve as the basis for the broad scope of the Hamilton Standard product line. The solid polymer electrolyte is simply a sheet of plastic material having a thickness of 5 to 10 mils. This ion exchange material is very similar to Teflon but has sulfonic acid groups attached to the side chains to allow for ion transport.

TEFLON

$$—(—CF_2—CF_2—CF_2—)—$$

SOLID POLYMER ELECTROLYTE



The material presently in production is a perfluorocarbon polymer, Nafion, and is produced by DuPont.

The use of the solid polymer sheet as the principal electrolyte in an electrochemical cell offers the following advantages:

- High Efficiency
- High Reliability
- Low Weight
- Long Life
- System Safety
- Mechanical Integrity and Chemical Stability
- Compactness
- Ease of Handling During Assembly and Maintenance

- Capability of Sustaining High Pressure Differentials Across the Electrolyte

- No Tendency to React with CO_2 to Form Carbonates

Physically bonded on each side of the electrolyte are thin catalytic electrodes which support electrochemical half-cell reactions. For the hydrogen/oxygen fuel cell cathode (oxygen electrode), a thin wetproofing film is placed over the electrode in order to prevent product water from obstructing the active surface.

The performance of these electrode structures has been tested for over 60,000 hours in a hydrogen/oxygen fuel cell life test, with minimal performance degradation. The specific voltage decay rate is less than one microvolt per hour at a current density of 100 amps per square foot (ASF).

Development of the SPE fuel cell product line began during the 1950's and has been steadily pursued ever since, for a continually widening range of applications. The SPE electrolysis product line was initiated in the late 1960's with the advent of long life fluoropolymer electrolyte membranes. Since that time the SPE electrolysis product line, like the SPE fuel cell product line, has also been developing. The cumulative development experience, as described in Appendix A, forms a significant portion of the technology base.

Over the thirty years of development of SPE fuel cells there have been three major innovations that have brought the SPE fuel cell to its current status:

- Introduction of DuPont's Nafion membrane
- Introduction of porous cathode wetproofing
- Introduction of electrically conductive porous cathode wetproofing

Countless improvements have been made over the years, however, the above three innovations have provided a most significant impact.

<u>Nafion Membrane</u> - The NASA Gemini spacecraft utilized the first space fuel cell, an oxygen/hydrogen SPE fuel cell. This SPE fuel cell was successful only because the mission life requirements were short (<500 hours) and the

operational temperature was low. The polystyrene sulfonic acid membranes used at that time chemically degraded in the hydrogen/oxygen environment such that all useful life was expended in about 1000 hours at room temperature. Cross cell leakage developed as a result of the chemical attack of the membrane, and cell stack voltage and current fell to zero.

The Biosatellite SPE fuel cell had a higher operational temperature requirement and a longer mission life requirement (>1000 hours) than did the Gemini fuel cell. The requirements were met by the introduction of the Nafion membrane. The very first Nafion membranes decreased the chemical attack rate and improved membrane useful lifetimes by approximately two orders of magnitude. Over the years since the Biosatellite program, further increases in useful lifetimes have been obtained through improvements in the basic membrane material, in cell fabrication techniques and in refinements cf operational conditions.

Wetproofing - A shortcoming of both the Gemini and Biosatellite fuel cells was the very low current density capability (<50 ASF). The low current density resulted from partial cathode electrode flooding by the product water which inhibited oxygen gas from diffusing to a reaction site. In the late 1960's, a cathode wetproofing film was developed which significantly reduced the oxygen diffusion difficulties.

This cathode wetproofing film was introduced into the Space Shuttle SPE fuel cell technology program and the U.S. Navy's HASPA SPE fuel cell program. Current density capabilities several times the Gemini and Biosatellite fuel cells were obtained on these SPE fuel cell programs. However, these initial wetproofing films were not electrically conductive which made it necessary to collect the electrical current from the edge of the cells. This limited the useful current density to less than 250 ASF.

Conductive Wetproofing - A recent major step was perfected in the late 1970's and that consisted of the development of electrically conductive cathode wetproofing films. This development eliminated the need for cell edge current collection and allowed current densities in excess of 1000 ASF.

The history of SPE fuel cell performance and life capability are shown on Figures 1 and 2. The high current density achieved by today's fuel cells is attributed to the electrically conductive cathode wetproofing film used in combination with perfluorinated membranes like Nafion.

2.1 Naval Power Source Technology

SPE fuel cells have been used previously to power naval buoys. One such application was the development of a 1.8 kWH power system for the Naval Air Development Center. This completely sealed, self-contained fuel cell power supply was designed for operation in a subsurface, moored-buoy surveillance system. The development effort was for potential application in a "B" sized buoy configuration.

The unit consisted of three major subsystems: 1) Hydrogen generator; 2) oxygen generator; and 3) electrical subsystem. The electrical subsystem included a stack containing 35 series-connected fuel cells to provide continuous and pulse power with the associated controls for gas reactant flow and self-contained inert gas accumulation (produced by reactant gas generators). Hydrogen and oxygen for the fuel cell stack operation were obtained by chemical gas generation from stored solid chemical charges within the unit. The water produced during fuel cell operation was used in the hydrogen Kipp generator to react with stored sodium aluminum hydride ($NaAlH_4$) for hydrogen generation. Oxygen was generated by the ignition of a sodium chlorate candle ($NaClO_3$) initiated by a low oxygen pressure signal in the oxygen generator. This resulted in a sequential ignition of one of twenty-two packaged candle charges and liberation of a fixed amount of oxygen.

The hydrogen generator was activated by applying 24 VDC to the unit activation circuit. This permitted the startup charge of 31.5% KOH solution to contact the chemical charge within the Kipp generator for hydrogen liberation on demand. The oxygen generator was also activated simultaneously by closing the electrical circuit to the fuel cell stack.

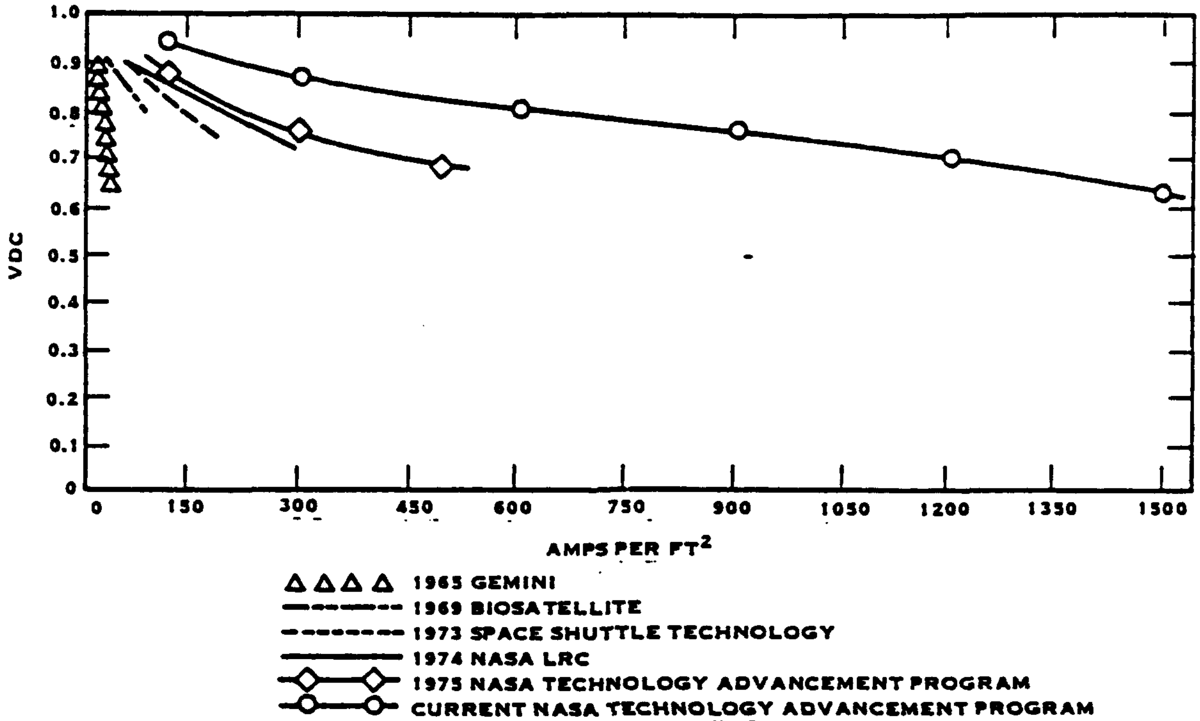


FIGURE 1. Fuel Cell Performance History

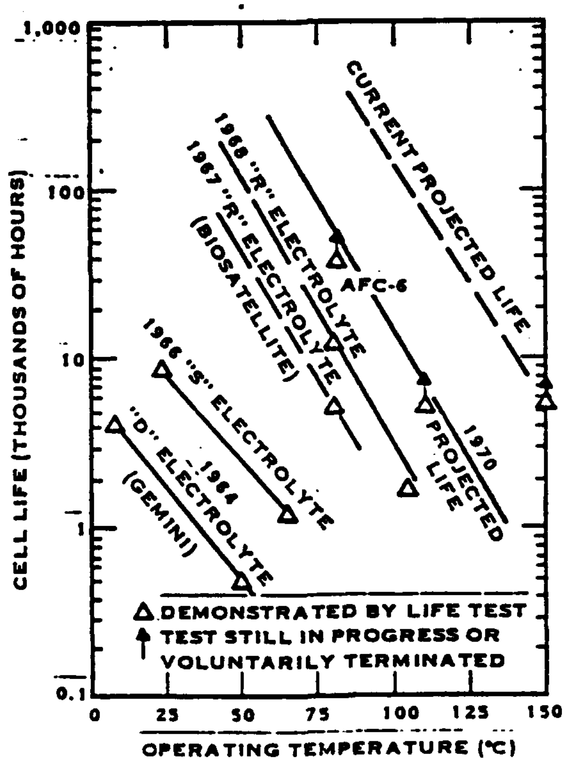


FIGURE 2. SPE Cell Life Capability

Figure 3 shows the complete power plant including gas generators, controls and fuel cell stack. Figures 4 and 5 show the sea water testing of the 1.8 kWH power plant. The overall system fluid schematic is shown on Figure 6. Design data for this power plant are as follows:

• Total unit weight fully charged:	23.9 Pounds
• Total watt-hour capability:	1844 watt-hours
• Energy Density:	77 watt-hr/lb
• Size:	6.625 inch dia x 8 inch high
• Continuous output power:	0.45 watt
• Pulse power capability:	7.9 watts for 30 minutes/day
• Voltage regulation:	29 ± 4 VDC
• Operating temperature range:	27 to 120°F
• Storage temperature:	-65 to +160°F
• Max. internal oxygen generator pressure:	800 psia
• Operating life:	90 days at rated power (limited only by size of fuel & oxidant charge)

Testing of the 1.8 kWH fuel cell power plant was conducted both in the research laboratory and in the water at the St. Croix test site. Successful operation up to five continuous weeks was shown in the laboratory and approximately one week at St. Croix.

A 44 kWH self-contained fuel cell power supply was also designed for operation in a deeply moored, buoy surveillance system. This effort was under contract to Sanders Associates, Inc. for potential application as a power supply in a buoy system concept developed for the Naval Air System Command. The unit consisted of three major subsystems: 1) Hydrogen generator; 2) oxygen generator; and 3) electrical subsystem. The electrical subsystem included of a stack containing six series-connected fuel cells to provide the continuous output power and the power required to recharge a NiCd battery. Unlike the 1.8 kWH power plant, a battery was provided for the buoy system pulse load

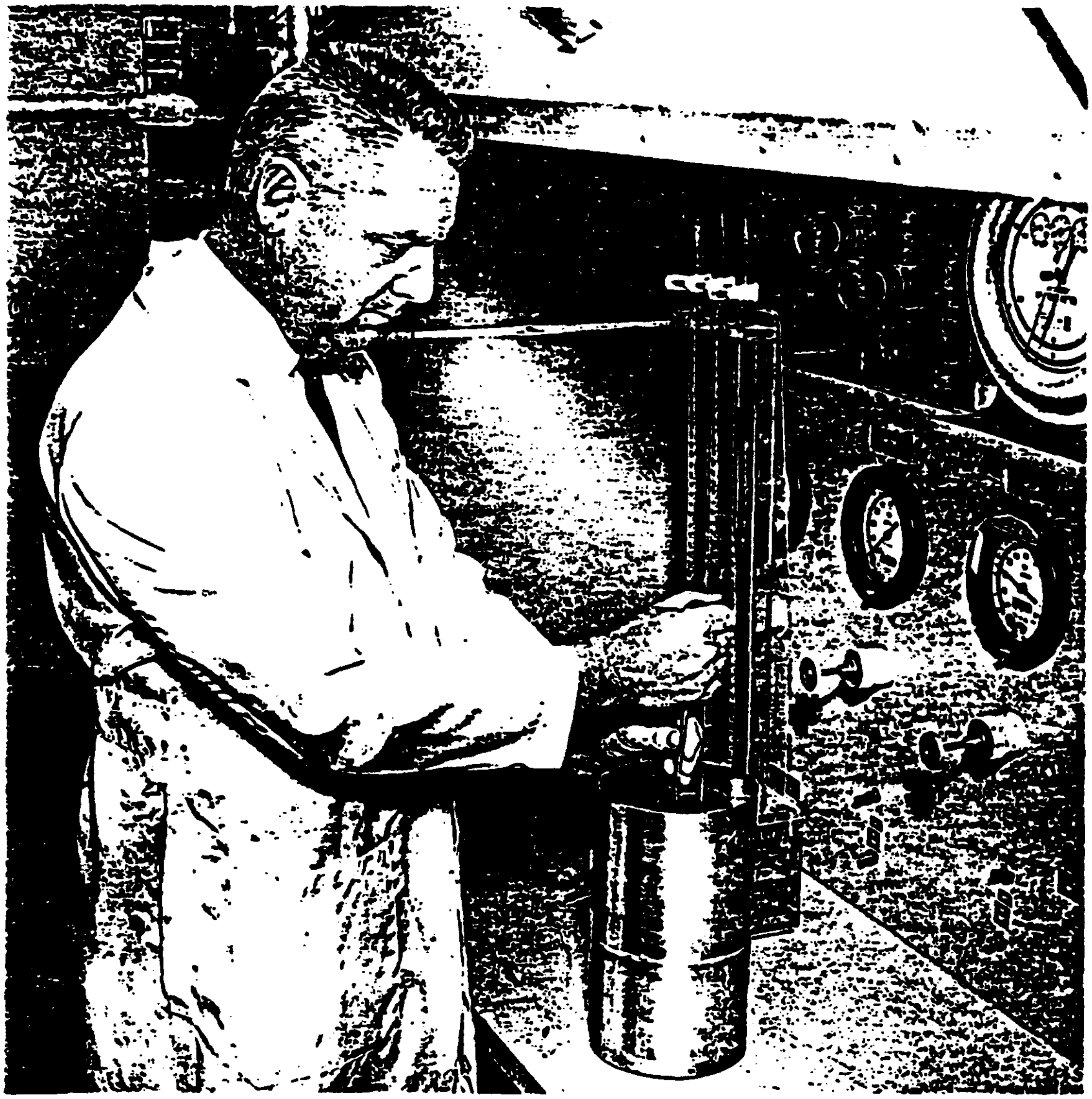


FIGURE 3. 1.8 kW Power System

FIGURE 4. Seawater Testing of 1.8 kW Unit

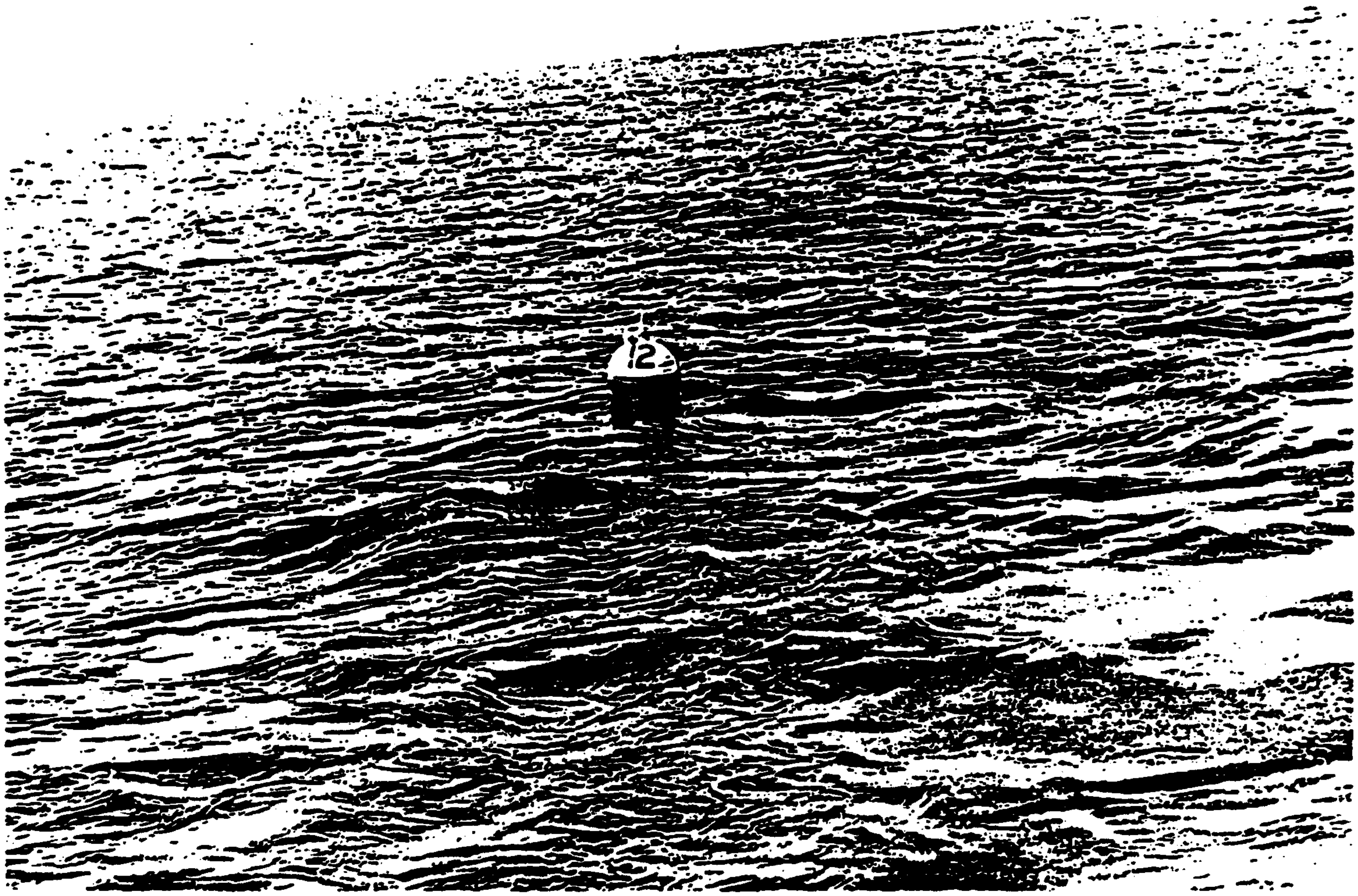


FIGURE 5. Seawater Testing of 1.8 kW Unit

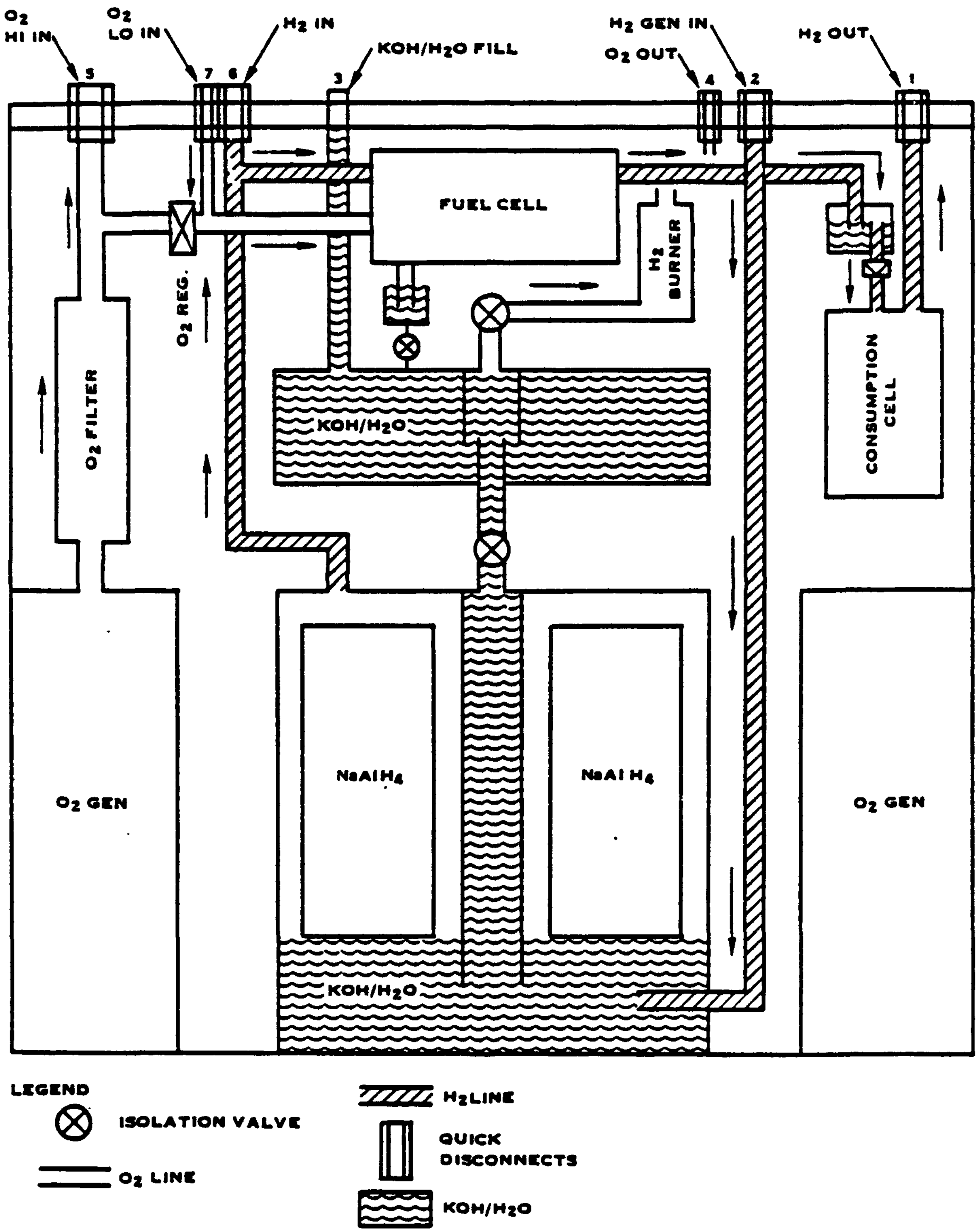


FIGURE 6. Fluids Schematic of 1.8 kW Power System

requirements. The battery was necessary for the required 500 watt peaks due to the current density limitations of the 1967 fuel cell technology. At that time a 500 watt fuel cell stack alone would have required a volume of more than 3 $Ft.^3$ and would have had a weight of greater than 75 pounds. The generation of hydrogen and oxygen in this system was the same as that for the 1.8 kWH unit, except that greater fuel and oxidant quantities were provided. This unit could also be operated with external bottle gas supplies.

A sketch of the 44 kWH self contained buoy fuel cell power plant is shown in Figure 7. The system design data was as follows:

• Total unit weight fully charged	313 Pounds
• Total watt-hour capability	44,000 Watt-hours
• Energy density	140 Watt-hours/pound
• Size	18" dia x 18.3" high
• Continuous output power	5 watts
• Pulse power capability	500 watts for 2 seconds/hr
• Voltage regulation	3 ± .2 VDC
• Operating temperature range	27 to 120°F
• Storage temperature range	-65 tp +160°F
• Max. internal oxygen generator pressure	150 psia
• Operating Life	One year continuous at rated power (limited only by size of fuel and oxidant charge)

2.2 SPE Fuel Cell Fundamentals

The membrane electrolyte used in the SPE fuel cell is a solid plastic sheet of perfluorinated polymer about 10 mils thick, having many of the physical characteristics of Teflon. Since this polymer has sulfonic acid groups chemically bonded to it when saturated with water, it acts as an excellent ionic conductor and is the only electrolyte required in the fuel cell system. Ionic conductivity is provided by the mobility of hydrated hydrogen ions ($H^+ \cdot X\, H_2O$). These ions are conducted through the membrane by passing between the fixed sulfonic acid groups; therefore, the concentration of acid remains constant within the polymer and system electrolyte need not be replenished. The polymer sheet is known as an ion exchange membrane (IEM). Being a tough plastic (Figure 8), it also provides reliable separation of reactant gases.

A typical cell is shown in Figure 9. This represents a cross-sectional view through the SPE cell with the attached electrodes depicted on either side of

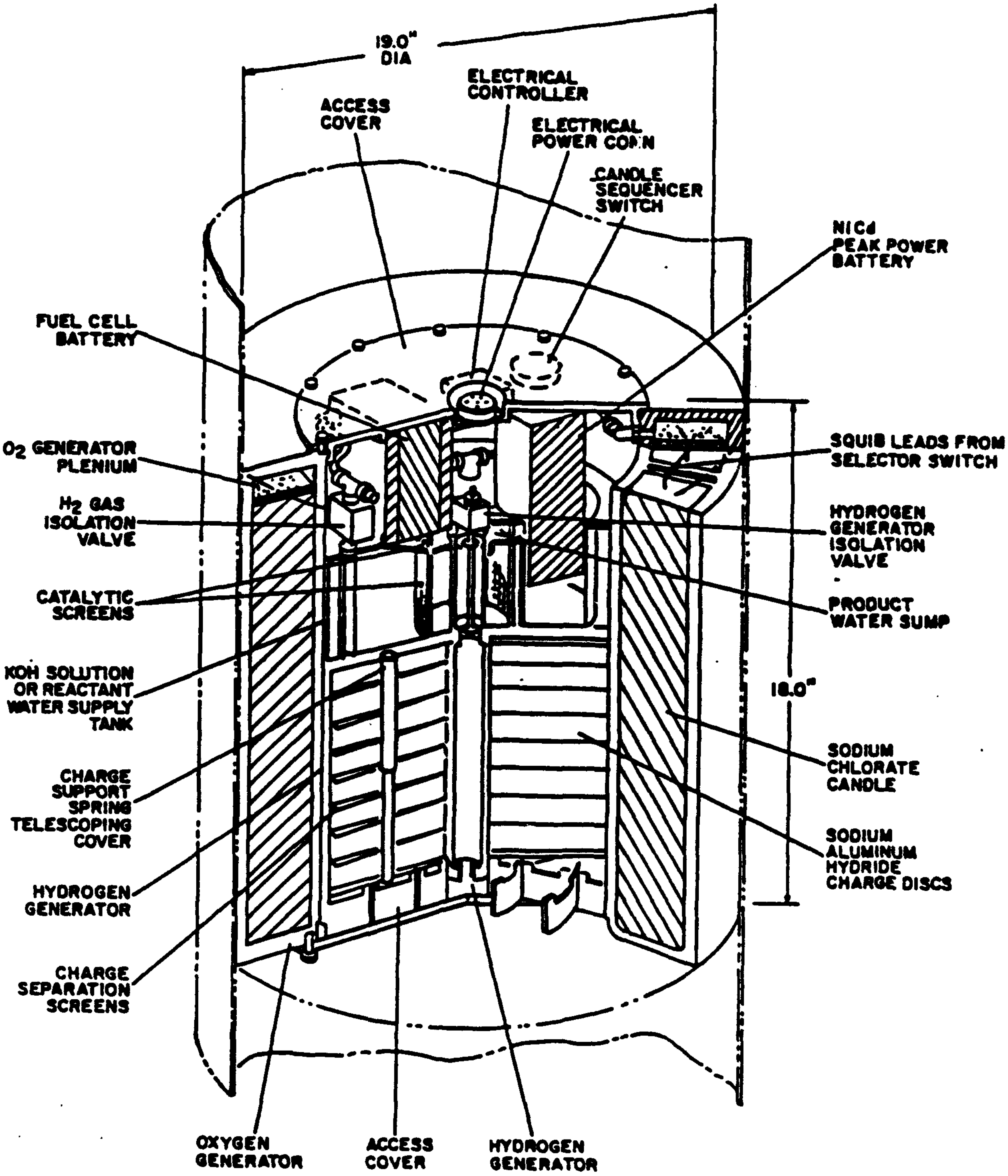


FIGURE 7. 44 kW Buoy Power System

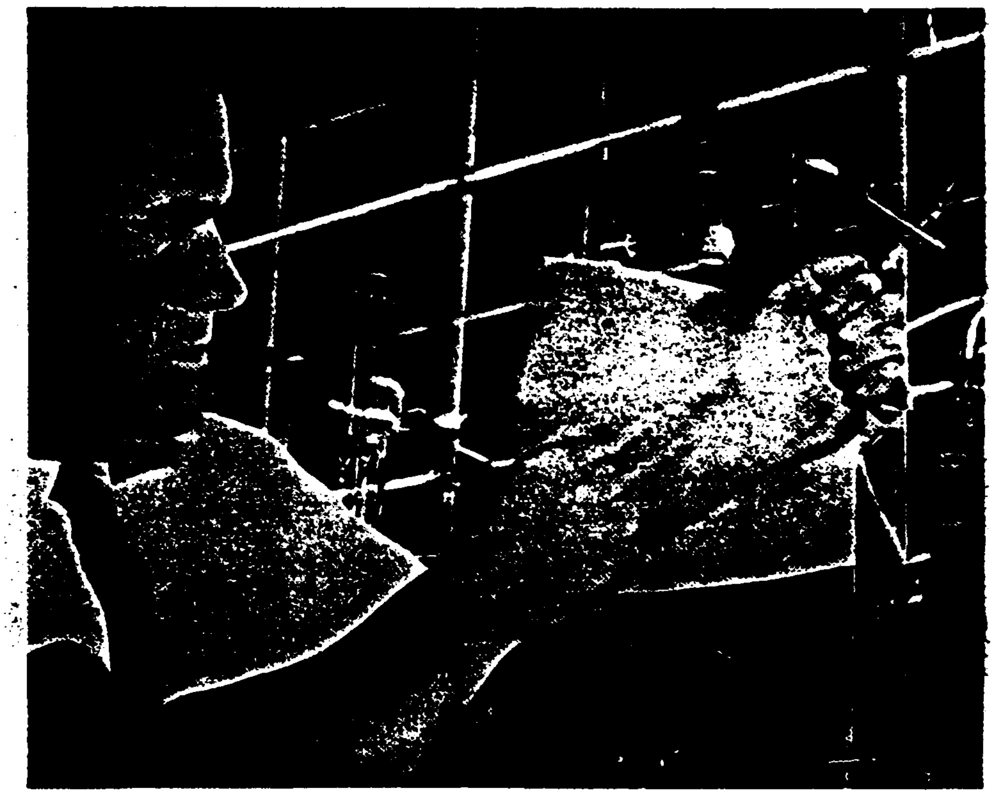
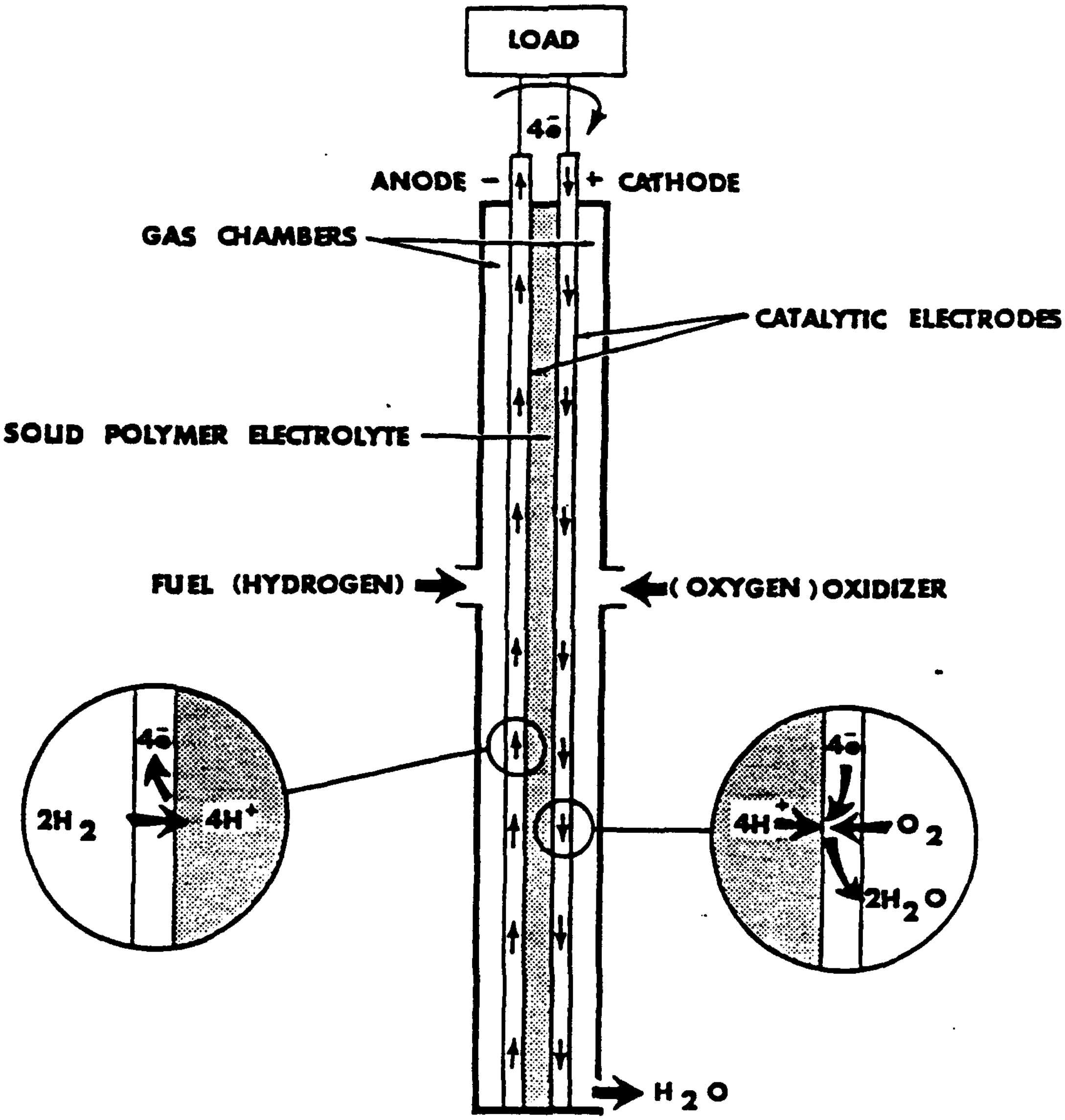


FIGURE 8. Solid Polymer Electrolyte Membrane



SOLID POLYMER ELECTROLYTE FUEL CELL

Figure 9. SPE Hydrogen/Oxygen Fuel Cell

the membrane. Oxygen and hydrogen gases are supplied to the oxygen electrode (cathode) and hydrogen electrode (anode) respectively in the fuel cell. The electrodes consist of high surface area catalytically active materials which support the electrochemical reactions.

Hydrogen gas is consumed by an electrochemical half-cell reaction in which hydrogen ions ($4H^+$) are produced and electrons are released to the external circuit for driving an electrical load. At the cathode, the hydrogen ions and electrons participate in an electrochemical reaction along with reactant oxygen to form pure water. Liquid water is prevented from filming, which would mask reaction sites, by application of a hydrophobic film to the oxygen electrode. The product liquid water is removed from each cell either by gravity, a porous plate separator or by flowing excess oxygen gas through the cathode chamber.

2.3 Parametric Effects

The electrochemical reactions for the hydrogen/oxygen fuel cell are depicted in Figure 10. At the fuel cell anode, oxidation of hydrogen occurs, forming protons and electrons according to the half reaction:

$$H_2 = 2H^+ + 2e^-$$

Protons are conducted through the IEM with the electrons passing along the electrocatalyst to the external circuit. At the oxygen electrode, reduction occurs. The protons, oxygen and electrons are consumed in the other half reaction:

$$4e^- + 4H^+ + O_2 = 2H_2O$$

From the free energy of the reaction, one predicts the open circuit potential of such a cell to be 1.23 volts with a pressure of one atmosphere absolute for both gases. Agreement of theory and practice has not been realized, probably due to electrode/interface phenomena. Actual open circuit voltage of the hydrogen/oxygen fuel cell is closer to 1.00 volts, and is quite repeatable.

SPE FUEL CELL SCHEMATIC SHOWING ELECTROCHEMICAL REACTIONS

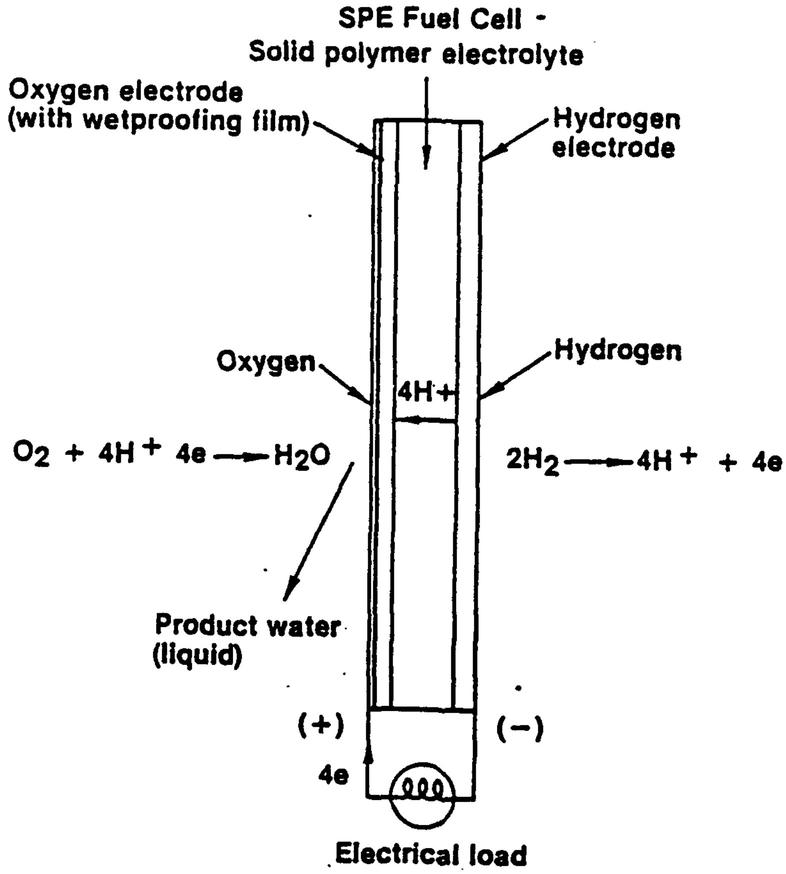


FIGURE 10. Electrochemistry of the Hydrogen/Oxygen Fuel Cell

Thermodynamics also predicts that the cell voltage will increase with an increase in reactant pressures. In practice, this result is generally attained to pressures of 100 psig. Reactants will diffuse through the IEM in a linear relationship with pressure. The dependence of reactant diffusion on pressure is nearly linear. Thus, at pressures above 100 psig further efficiency increases are not realized, as reaction efficiencies are offset by loss of reactants across the membrane.

The theoretical open circuit voltage decrease for the hydrogen/oxygen fuel cell, due to an increase in operating temperature, can be calculated with the use of the following equation:

$$\Delta F = [CpT\ (\ln T - 1)]\Big|_{T_1}^{T_2}$$

Where ΔF is the change in free energy, which is proportional to the cell voltage:

Cp is the specific heat of product water
T is the temperature
T_1 is the absolute temperature, 25°C = 298°K
T_2 is the final temperature, °K

Thermodynamic effects are not the only factors which influence cell voltage when the cell operating temperature increases. The membrane resistance decreases with an increase in temperature and reactant gas diffusion also increases. Also, at very high temperatures (>250°F), product water vapor pressure limits oxygen reactant pressure at the electrode surface, creating a negative effect on cell voltage when operating at approximately 100 psi.

The additive effect of all factors result in a moderate increase in SPE hydrogen/oxygen fuel cell performance with temperature to approximately 140°F to 180°F. Above this range, positive temperature effects on cell voltage and efficiency are severely diminished.

Based on this information, we can conclude that the fuel cell should be operated with reactant pressures of 90 - 100 psia if system constraints permit. Also, the cell temperature should be as high as possible without resulting in excessive reactant diffusion or cell degradation. A conservative envelope proves to be 140°F - 180°F. These conditions allow for high efficiency, long life operation of the fuel cell. The performance of cells configured from two different Nafion formulations (117 and 120) under these operating conditions are shown in Figure 11.

3.0 MISSION REQUIREMENTS

The Deployable Acoustic Projector Source fuel cell power system is required to provide power reliably over the length of the mission. The mission power requirement is 400 kW for two-second durations or 100 kW for ten-second durations. The total mission power requirement is 132 kW Hr.

Additional requirements are that the power source be safe, easy to operate, reliable and cost effective. The system must be easily and rapidly recharged and must be easily configured to fit within the anticipated volume envelope. It is assumed that this system should be as small and lightweight as possible yielding a high energy density, and that acoustic emission be minimized.

4.0 POWER SYSTEM OPTIONS

Near term power system requirements can be attained by adapting existing fuel cell technology to meet the power system specifications of the DAPS. Present "off-the-shelf" module designs vary only in active area and mode of electrical current and fluids distribution. The design of the membrane electrode assembly remains fixed, although substitution of membrane materials having differing physical properties represents an option. A description of each general type of fuel cell hardware follows:

<u>0.23 Ft.^{2} Screen Type</u> - This type of electrochemical device hardware, shown in Figure 12, has proven versatility and reliability. The membrane electrode assembly forms the heart of the cell design. The oxygen electrode has a conductive wetproofing film attached in order to prevent water buildup on the

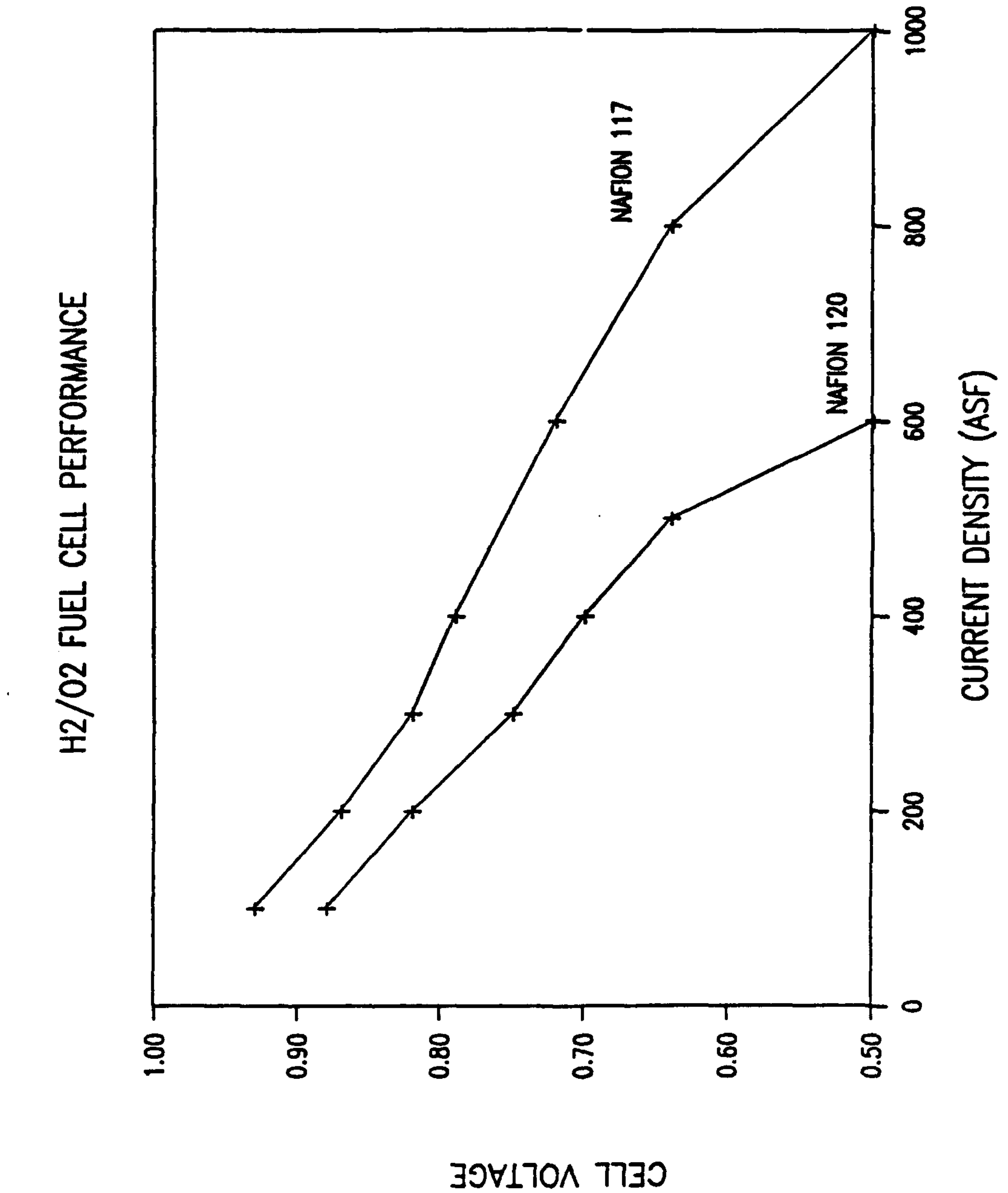


FIGURE 11. Performance of the Hydrogen/Oxygen Fuel Cell

FIGURE 12. 0.23 Ft.³ Cell Hardware

surface of the catalyst. A package of niobium screens is placed in intimate contact with the membrane electrode assembly, thus forming a means for reactant and product transport as well as current distribution. A circular polysulfone frame surrounds this screen package, affording a means for overboard sealing. A similar screen package and frame design placed on the alternate side of the membrane forms the hydrogen cavity of the cell. This screen package is constructed from niobium due to its proven durability in the hydrogen environment. Cell units are assembled in bipolar fashion, with a conductive separator sheet placed in between. A schematic of a typical cell assembly is shown in Figure 13.

Because of its proven reliability, this hardware design is presently being field evaluated for the U.S. Navy and is being used by the Royal Navy for oxygen generation in nuclear submarines. In addition, the 0.23 $Ft.^2$ cell configuration is being modified for high pressure oxygen recharge of space suits and also electrolysis for space station propulsion fuels. Fuel cells have been developed, based on this design, for pulse power Naval Buoy applications.

Electrochemical stacks having 80-100 cells are manufactured routinely at Hamilton Standard. This hardware has proven durability, in that single-cells have been run for more than 90,000 hours, showing minimal voltage degradation. Fully assembled stacks have run for tens of thousands of ampere hours showing excellent performance. 100-cell modules have been qualified for high shock and vibration operation.

<u>0.78 $Ft.^2$ Screen Type</u> - The 0.78 $Ft.^2$ circular screen type fuel cell hardware is presently being developed for Naval vehicle and buoy power supply applications. This hardware features a large active area which allows for low current density, high efficiency operation. The circular shape provides excellent sealing capability in multi-cell stacks and also promotes even heat and current distribution. This hardware represents a scaled-up version of the present production 0.23 $Ft.^2$ hardware, and therefore will exhibit the excellent sealing and stackability characteristics of the production hardware.

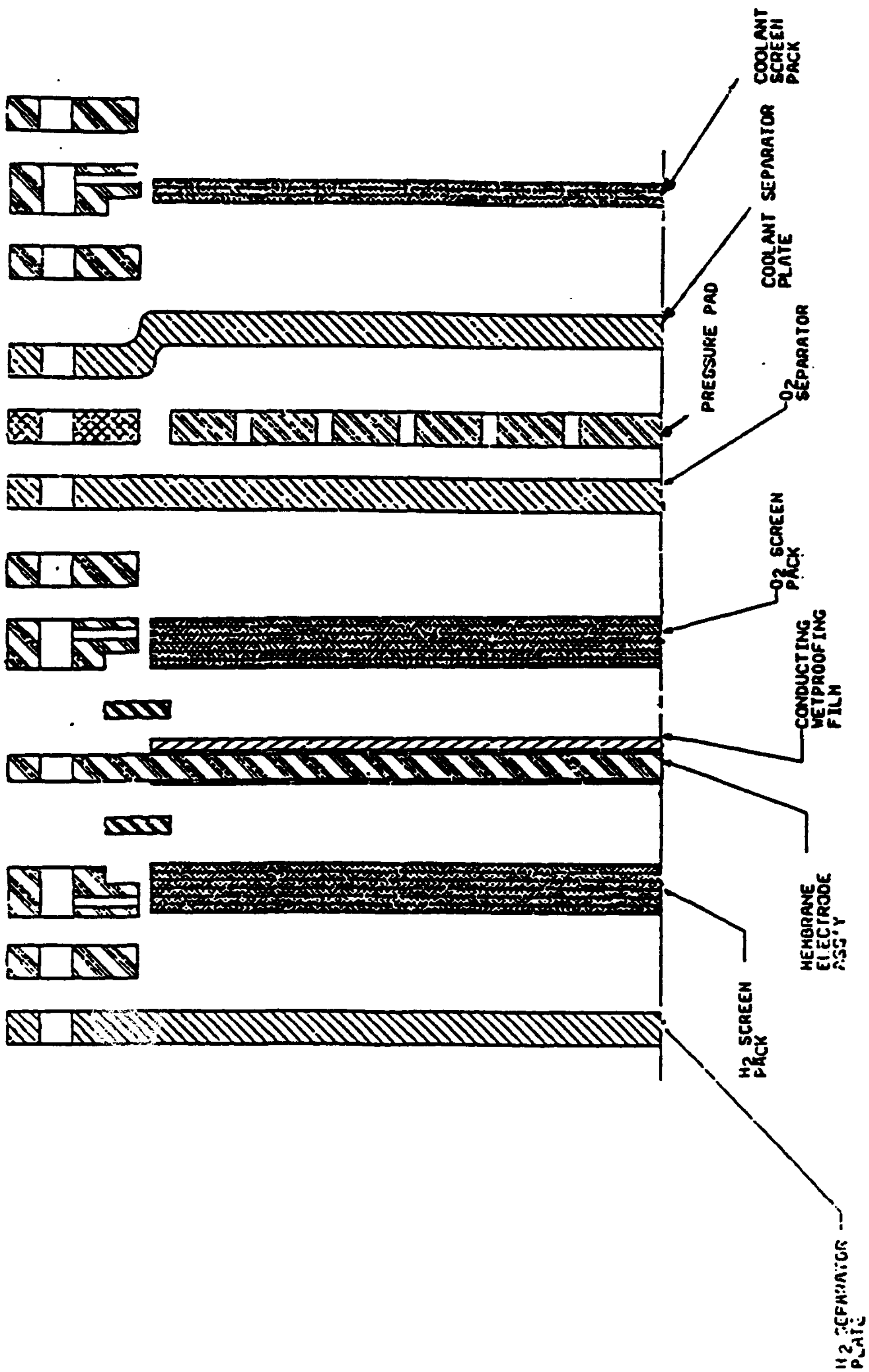


FIGURE 13. Cell Assembly Schematic

0.9 Ft.² Sheet Metal - The 0.9 Ft.² square sheet metal hardware was originally designed for low weight space fuel cell applications. It consists of a stack of individual fuel cell assemblies each 0.100 inch thick, one of which is illustrated in Figure 14. Its various layers consist of the cell membrane having a thickness of 0.009 inch, a coolant cartridge and an anode support. The cell has a square pattern and the active surface for design rated conditions is 0.9 Ft.². The active surface is thereby 11.4 inches square.

Support plates outside the cell take the tensile load necessary to compress the stack, sealing the cell assemblies to each other. The largest of these stacks consisted of 15-cells and was constructed for a NASA regenerative fuel cell application.

1.0 Ft.² Graphite Cells - This type of hardware, shown in Figure 15, was originally developed for commercial electrolysis applications and thus offers the potential for low cost construction. In this configuration, a wetproofed electrode support bonded to the oxygen electrode provides electrical continuity as well as fluids passage between the electrode surface and current collector flow field. The current collector is fabricated from a conductive graphite composite and has flow passages molded into each side. A conductive electrode support bridges the gap between the hydrogen flow field and the membrane and electrode assembly. The cells in a stack are arranged such that each hydrogen and oxygen compartments are alternately separated by a membrane and a current collector. A fuel cell developed for Deep Base applications, which utilizes this hardware, is shown in Figure 16.

The potential of the 1.0 Ft.² graphite hardware for low cost has made this design attractive for vehicular applications. Electrolyzer stacks having up to forty-cells have operated efficiently at high current density for tens of thousands of hours. Cells configured for bulk hydrogen generation have successfully operated to currents of 2500 amps with minimal voltage variation.

The brittleness of graphite hardware does not lend itself to applications requiring moderate shock loads. For this reason, graphite hardware will not be considered for the DAPS.

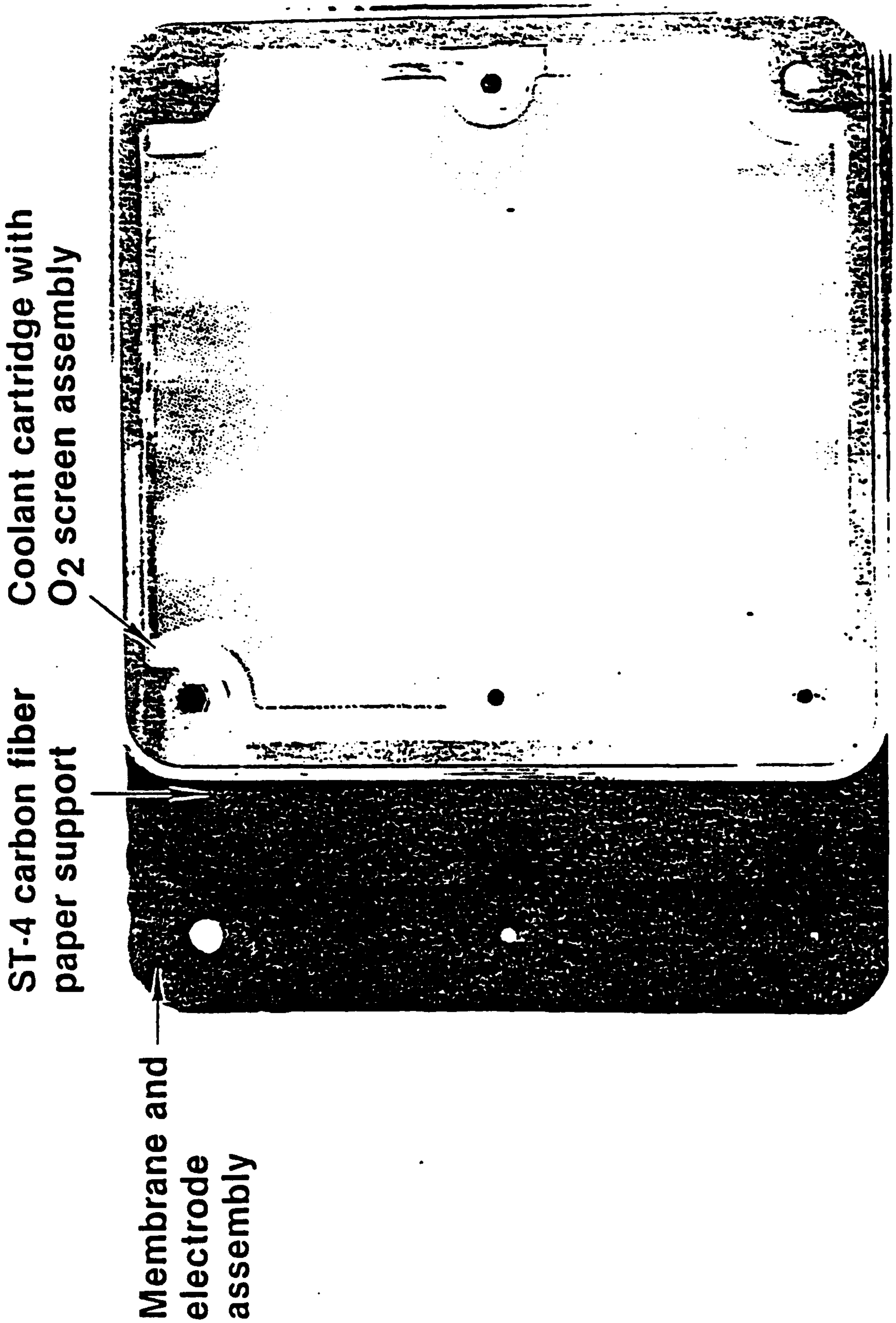


FIGURE 14. 0.90 Ft.[2] Cell Hardware

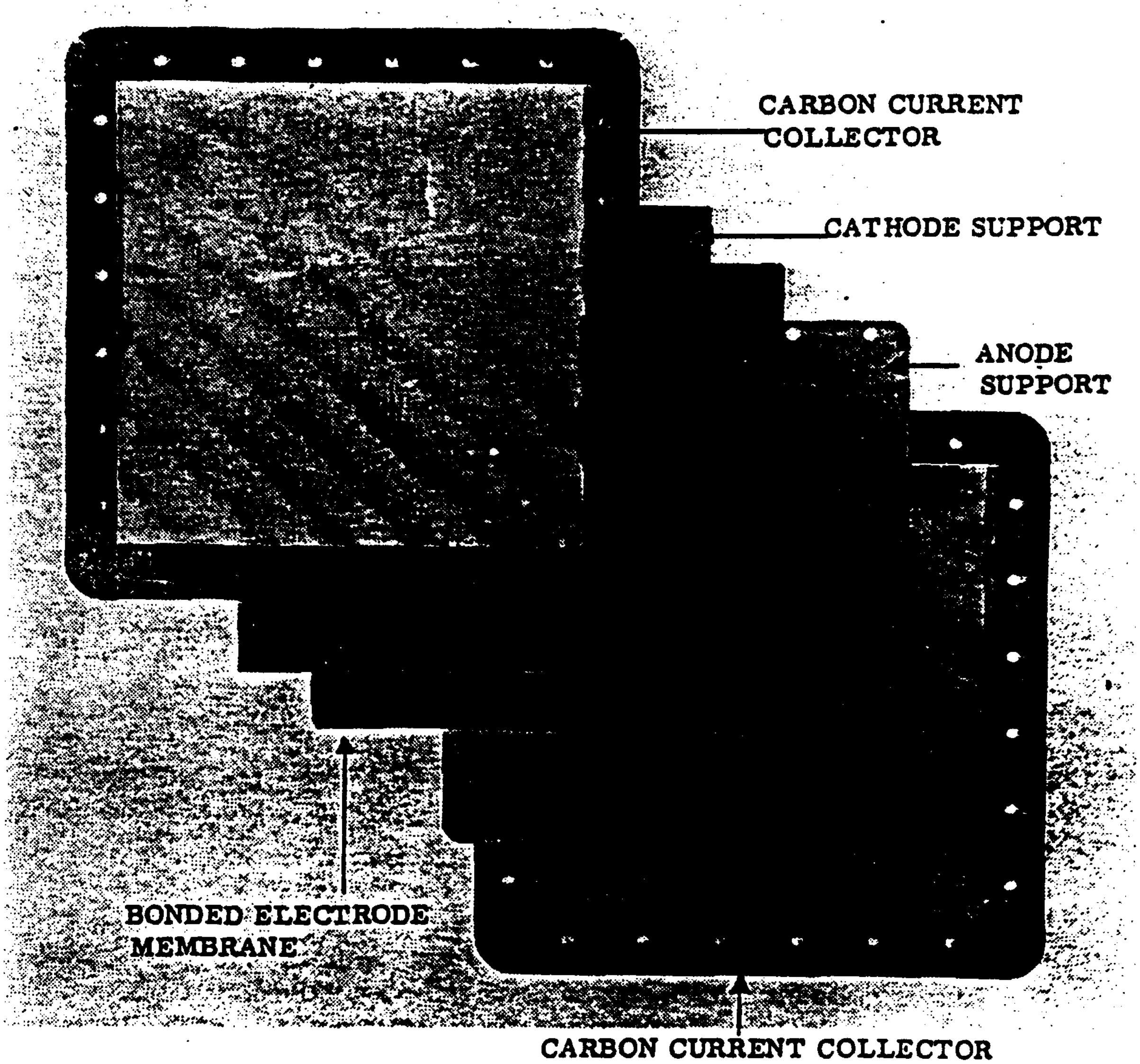


FIGURE 15. 1.00 Ft.² Cell Hardware

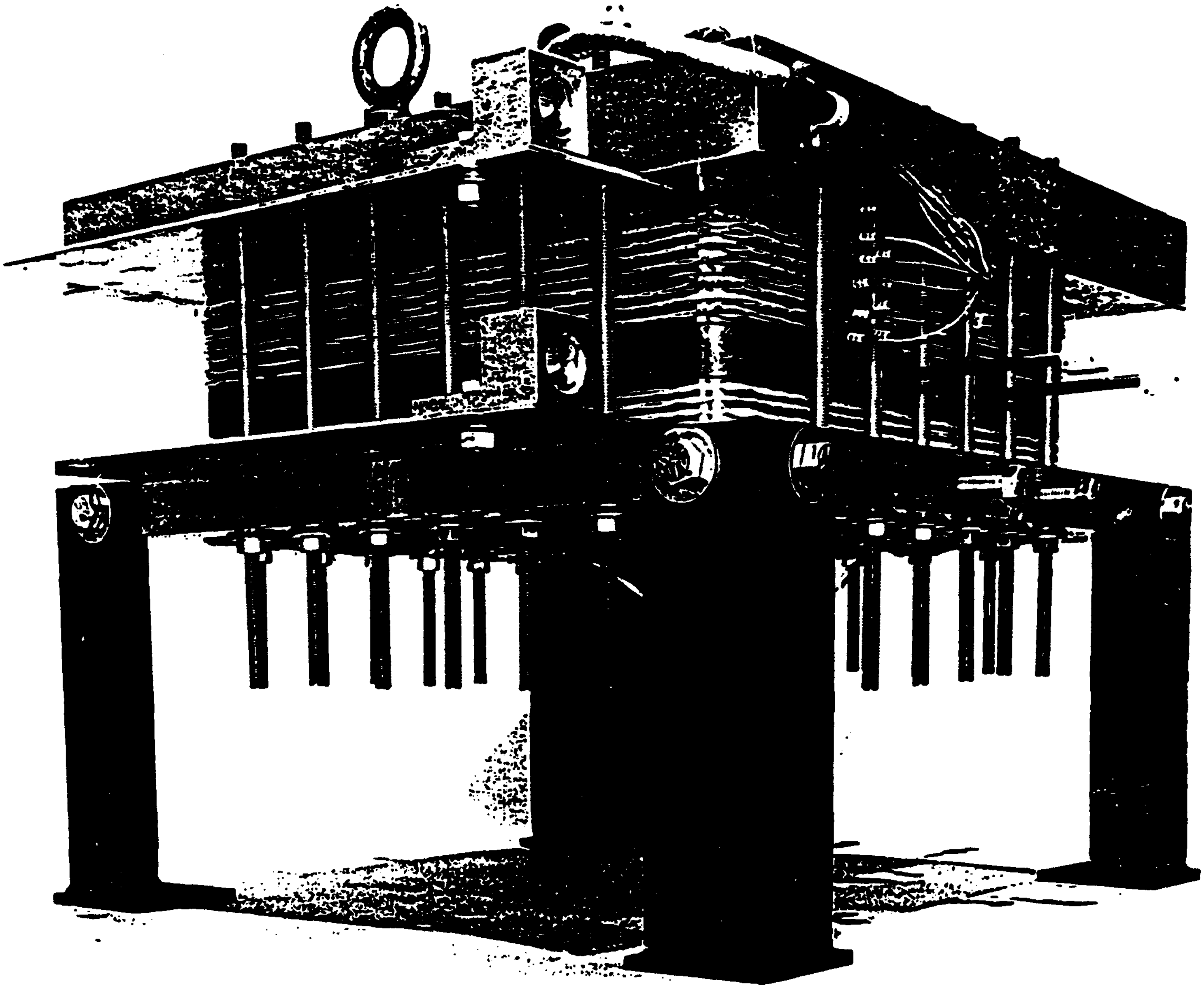


FIGURE 16. Prototype Hydrogen/Chlorine Fuel Cell

Considerations for Design Selection - The ease with which cell hardware may be modified allows for the fuel cell design to be tailored to the exact DAPS application. In this manner, every element of the fuel cell module could be designed in such a way so as to minimize cost while maximizing power system efficiency and energy density.

Water Removal - Removal of product water is a critical issue when considering fuel cell performance. Water can be removed by a variety of means in the SPE fuel cell, each means having differing systems implications: By gravity induced phase separation, by porous plate technology, by passing excess oxygen past the cathode, and by utilizing coolant flow to produce a venturi effect.

Heat Removal - Heat generated from the fuel cell reaction may be removed either actively or passively. An active system uses a coolant such as water to serve as a heat transfer fluid. The water is pumped past the cathode of each cell to an external heat exchanger.

Product fuel cell water may be used in this case to minimize system complexity and volume. A passive heat removal system utilizes a cooling plate which is placed within each cell in the fuel cell module. This plate offers a means by which heat may be conducted away from the module to either a thermal mass, or to an external heat exchanger.

5.0 POWER SYSTEM DESIGN DESCRIPTION

The DAPS fuel cell power system will consist of a fuel cell module, reactant storage, a fluids piping system and an electrical control system. Each will be described in more detail as follows:

Fuel Cell Module - The fuel cell module is an electrochemical reactor which provides an efficient means of electrical power generation. The fuel cell module is in actuality an assembly of individual cells which consume reactant gases while producing direct current. Higher current capability is afforded by increasing the active area of each cell while an increase in module voltage is attained by adding cells to the stack. Module current and voltage vary according to power demand.

Reactant Storage - The SPE fuel cell utilizes hydrogen gas as the fuel and oxygen gas as the oxidant. Reactant storage is achieved via utilization of commercially available pressure vessels, cryogenic tanks, metal hydrides or chemical storage means. Because of the stoichiometry of the overall electrochemical reaction, twice as much hydrogen is consumed during operation of the fuel cell as is oxygen. Therefore, twice as much hydrogen must be Ostored for the mission than oxygen. Also, the product water is easily stored in a separate tank or expelled overboard.

Fluids Piping System - Operability of the power system requires that reactants be delivered to the fuel cell from storage while product water is simultaneously removed. This is achieved by utilizing an arrangement of environment compatible tubing along with fluids regulation and control equipment. These components include gas regulators, solenoid valves and shutoff valves. The fuel cell module consumes reactants on demand; therefore, system control requirements are minimal.

Electrical Control System - The electrical control system consists of a controller, relays, etc., which provide for safe, reliable control of the fuel cell power system. This system controls the flow of reactants and products during start-up, shutdown and load transients. Power system status and control are provided by a control and display module.

The general system components arrangement is shown in Figure 17. This shows the major system components and also provides some information regarding system arrangement. The specific system schematic is depicted in Figure 18.

6.0 FUEL CELL MODULE DESIGN

The fuel cell module represents the heart of the DAPS power system. The SPE hydrogen/oxygen fuel cell module is comprised of several sets of repeating elements which function as individual cells, and additional segments which facilitate stack compression, fluids and electrical distribution and reactant humidification. Each segment will be described in detail in the following sections.

SYSTEM COMPONENTS ARRANGEMENT

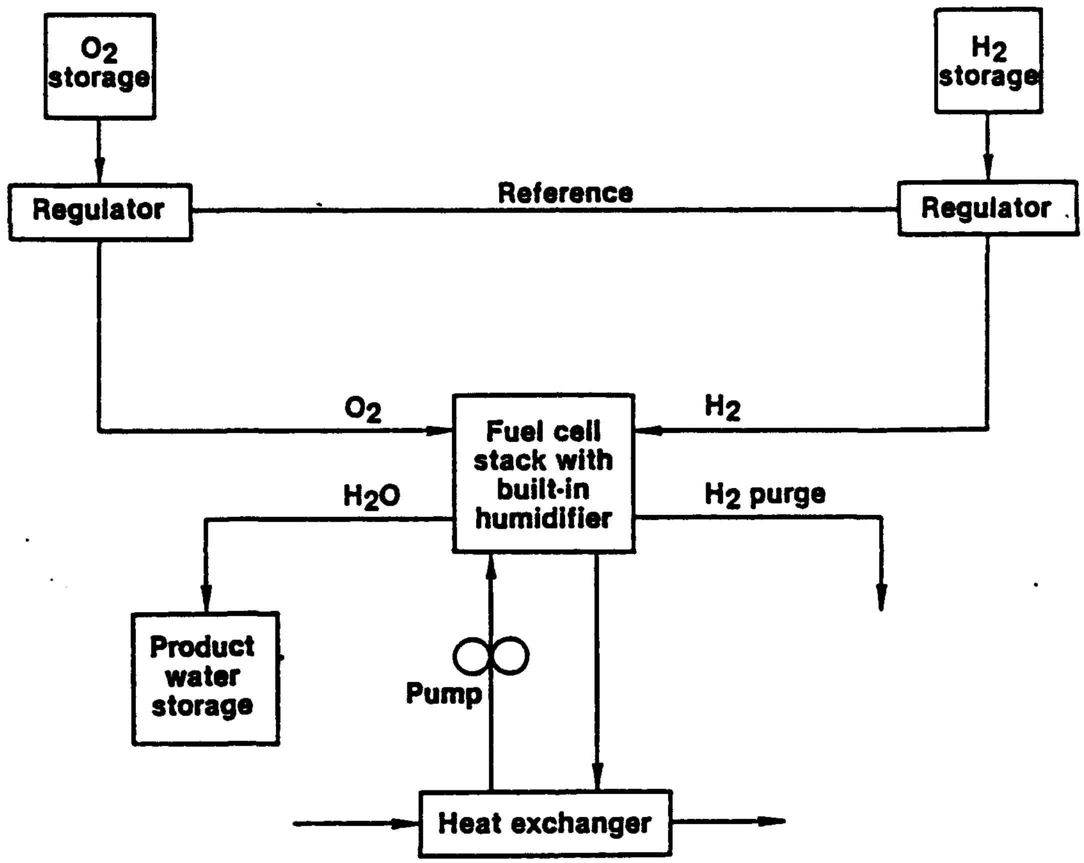


FIGURE 17. System Components Arrangement

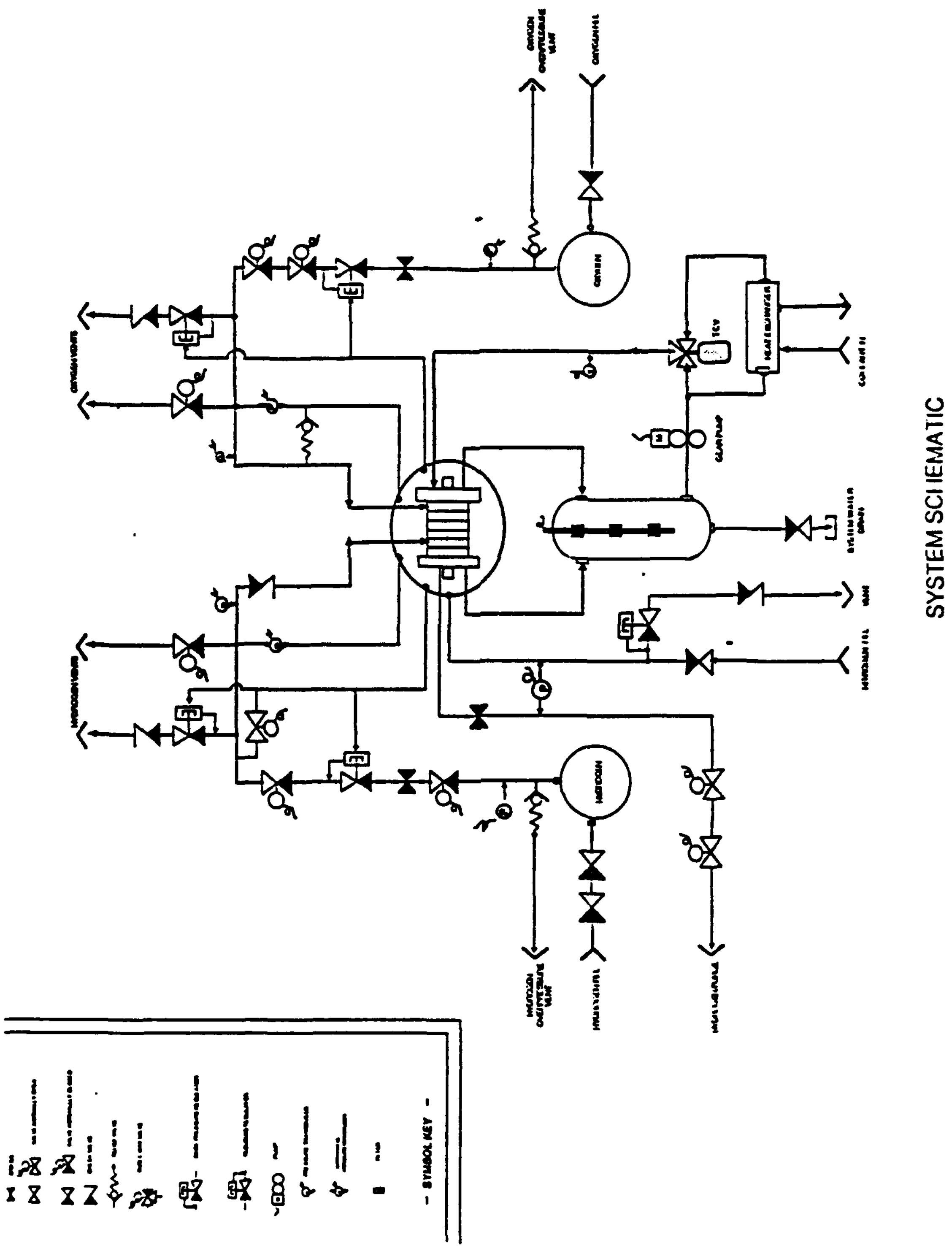


FIGURE 18. Power System Fluids Schematic

6.1 Cell Assemblies

To produce a multiple cell module, the repeating elements are stacked between end plates in a filter press fashion. Figure 19 displays a typical stacking arrangement. When the stack is compressed, the IEM forms a gasket seal around the internal manifolds.

In this design, each individual cell contains three compartments, one which contains hydrogen reactants, one which contains oxygen reactants, and one which passes cooling water. This cooling compartment need not be included if a passive cooling system is utilized. All are comprised of similar components, yet each is designed specifically for the necessary function. Each component represents only a minor modification of existing SPE cell technology. Each individual segment of the cell is described below.

Coolant Passage - Active Cooling

A coolant water passage may be provided to each cell in order to effectively remove the heat generated during operation. This coolant passage is simply constructed in the circular screen-type hardware with components which are used in the assembly. Manifolding of this coolant passage is afforded by polysulfone frames which contain small ports which communicate with the screened compartments. Electrical conductivity and fluids distribution are provided by a layered screen package. One side of the water fluid assembly chamber is formed by the solid niobium sheet that separates the water from hydrogen gas. The other side is also formed by a solid niobium sheet that separates the water from oxygen gas. The perimeter is sealed by a .060 inch thick polysulfone frame which provides both an overboard seal and internal fluid manifolds. The polysulfone frame has appropriately fashioned lateral holes to accommodate the flow of liquid water into and out of the active area of the cell. The active area of the water fluid assembly consists of a niobium expanded metal screen package and an electrically conductive compression pad.

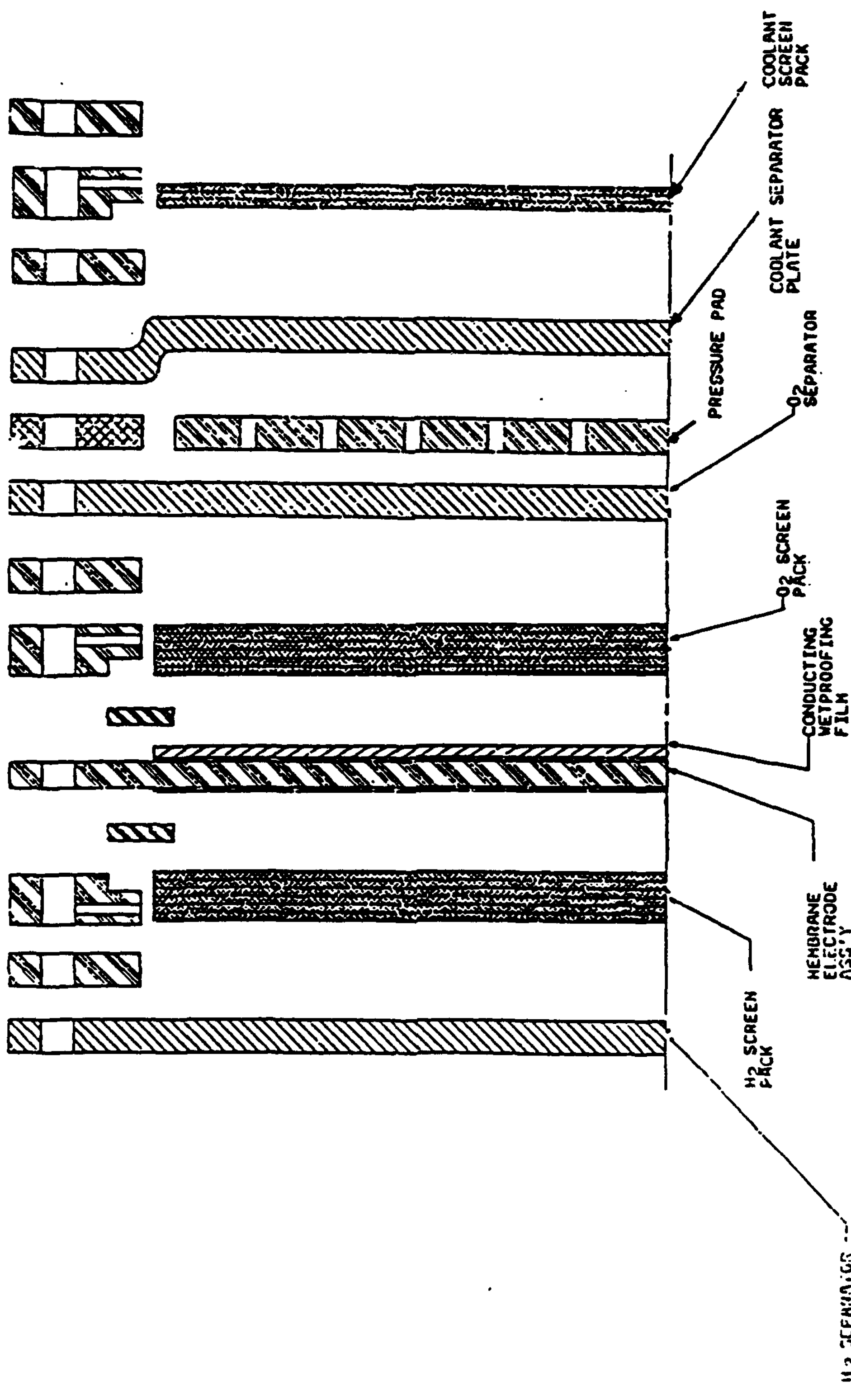


FIGURE 19. Component Stacking Arrangement

The electrically conductive compression pad is made from approximately .065 inch thick unfilled silicone rubber with multiple holes through its thickness. Niobium metal .003 inch thick is woven through the rubber. The functions of this component are:

- Provide uniform compression loading within the active area to maintain proper electrical conductivity
- Provide for conduction of electrons

The niobium screen package forming the water fluid assembly is made up of twelve layers of 0.005 inch thick niobium expanded screen. The major function of this component is to provide a low pressure drop passageway for the cooling water to pass through the cell. Additional functions include carrying electrons and accepting product water into the cooling water loop. The bulk cooling fluid, flowing between the compression pad and the hydrogen separator plate, automatically provides proper cell heat removal characteristics.

Cooling Plate - Passive Cooling

Provision for passive cooling within the fuel cell may also be included as an alternate design approach. This consists of extension of one or more of the niobium separator plates within the module to an external heat sink. This heat sink may be a water jacket, metal housing or other thermal mass. One convenient means of utilizing the excess heat is for the liberation of hydrogen fuel from metal hydride canisters for use in the subsequent reaction. Passive cooling of the fuel cell offers the advantage of having no moving parts within the system. This often enhances system reliability and reduces acoustic emission. One drawback is that passive cooling systems often do not have as much heat removal capacity as do active cooling systems, and therefore are commonly used in applications which require low current densities.

Oxygen Screen Assembly

The oxygen screen assembly represents a stack-up of expanded metal screens similar to those located in the coolant passage. Platinum plated niobium is used in this screen package due to its excellent corrosion resistance. The screen allows fluids and electrical current to be distributed uniformly over

the entire active area. This screen package is formed by welding the screens together to form a unitized component. The oxygen screen assembly is bounded on one side by a niobium foil which serves as a fluids separator and on the other side by the membrane/electrode assembly.

Hydrogen Screen Assembly

The hydrogen screen assembly provides a similar function to the oxygen screen assembly. In this case, niobium is also the material of choice due to its resistance to corrosion. The hydrogen screen assembly is bounded on one side by a niobium foil and on the opposite side by a membrane and electrode assembly.

6.2 Stack Compression

The cells, fluid distribution assemblies and product water separators are compressed between end plates connected by insulated tie rods. Belleville spring washers on the tie rods provide for thermal expansion and component creep and therefore maintain uniform compression over time.

The end plates have the major functions of maintaining a uniform compression load and collecting the current from the stack terminals. One end plate establishes a flat compression reference plane and provides the fluid interfaces between the fuel cell stack reactant prehumidification section and other fluid components of the system. The opposite end plate assists in stack compression. A load is applied to the stack for sealing the fluid ports and outboard frame and also for minimizing electrical contact resistance in the bipolar cell-stack configuration.

6.3 Reactant Humidification

Reactant humidification is necessary in order to minimize localized drying of the membrane in the fluids manifold areas. The humidifier of the fuel cell module, shown in Figure 20, automatically presaturates the incoming hydrogen and oxygen reactants to a dew point equal to the cell operating temperature and is essential for extended SPE fuel cell life.

END PLATE REACTANT PREHUMIDIFIER SCHEMATIC

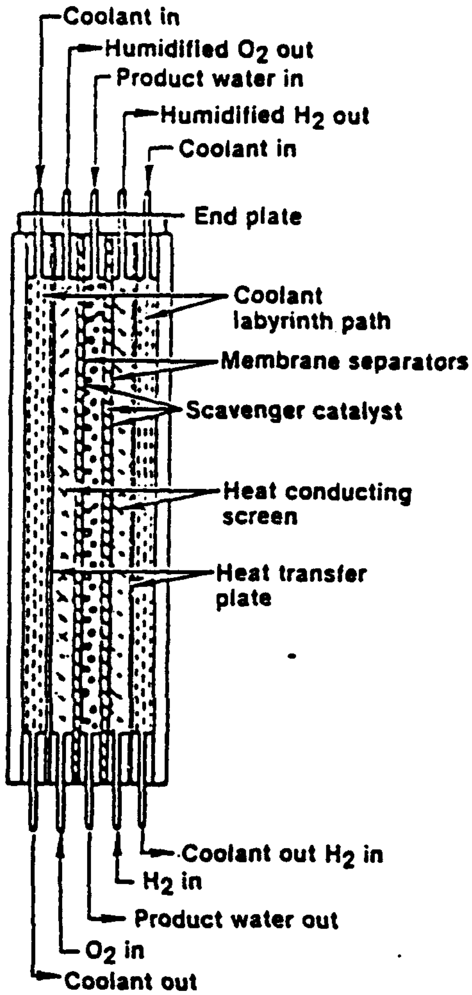


FIGURE 20. End Plate Reactant Humidifier

Transport of water to the incoming reactant streams is achieved by separating the reactants from a water source by means of a hydrated membrane having dimensions identical to those within the cell stack. Water is continuously and automatically transported across the membrane to humidify the reactants. Platinum catalyst materials are attached to either side of this membrane which serve as recombination sites for diffusing gases. The membrane is supported by niobium screen packages on either side while the reactant and water compartments are laterally bounded by polysulfone frames. Humidifier components are situated toward the reactant inlet end of the fuel cell module and all are compressed along with the cell components.

7.0 FLUIDS SYSTEM REQUIREMENTS

Oxygen is provided to the fuel cell module by means of an oxygen subsystem which contains tubing, regulators, valves, etc., to facilitate reactant control. In a similar manner, hydrogen feed is controlled by a hydrogen subsystem. Minimal system control is required because the SPE fuel cell consumes reactants on demand. A liquid water coolant subsystem which contains a heat exchanger, valves, pump and water storage container may be used to assist in fuel cell heat removal when passive cooling is inadequate. Water is manifolded from the fuel cell to a storage reservoir.

7.1 Oxygen Subsystem

Oxygen from the reactant supply is regulated to the desired pressure and introduced into the fuel cell module. Within the fuel cell module, the oxygen reactant is first humidified and then fed to the individual cells in parallel through the stack oxygen inlet manifold. Once in the cells, the oxygen reacts with hydrogen and product water is formed. The product water is fed from the oxygen fluid chamber to a storage vessel. The major oxygen subsystem auxiliary and monitoring components which are required include:

- Oxygen Supply Regulator
- Oxygen Supply Solenoid Valves
- System Relief Valves
- Oxygen Back Pressure Regulator
- Pressure Transducers

The oxygen subsystem is comprised of the oxygen storage and product water storage as well as any associated piping necessary for connection to the fuel cell module. The oxygen tankage can be filled by simply attaching an external oxygen source to the fill port. During operation, oxygen passes through a protective solenoid valve, through a nitrogen referenced regulator and finally through an orifice before entering the fluid plate of the fuel cell module. Product water is removed from either end of the module, and is fed by gravity to a storage vessel. This water can act as coolant and can be pumped through a heat exchanger via a thermal control valve and back to the fuel cell module. The coolant is passed across each cell and manifolded to the water storage vessel. All oxygen subsystem components are isolated from the environment by means of a vessel which is pressurized with nitrogen.

7.2 Hydrogen Subsystem

Hydrogen from the reactant supply is regulated, for safety reasons, to 25 psi below the oxygen pressure. Like the oxygen reactant, the hydrogen is humidified in the end plate humidifier and then delivered to the stack hydrogen manifold. The hydrogen flow in the fuel cell is directed through a cascading arrangement. This is necessary since reactants introduced to the fuel cell are generally not 100% pure. Normally inerts such as nitrogen, argon and some hydrocarbons are present in low concentrations. As reactants are consumed, diluent remaining in the system builds in concentration. The net effect is a slight reduction in operating voltage of individual cells. The cascaded system is arranged such that diluent is swept away from all but one cell in the module. When the stage four cell voltage falls to 0.60 volts, a short hydrogen purge is conducted, sweeping impurities out of the system either overboard or to an accumulation. A representative cascaded system is shown in Figure 21.

The major hydrogen subsystem components include:

- Hydrogen Supply Solenoid Valves
- Hydrogen Supply Regulator
- System Relief Valves
- Hydrogen Back Pressure Regulator
- Pressure Transducers

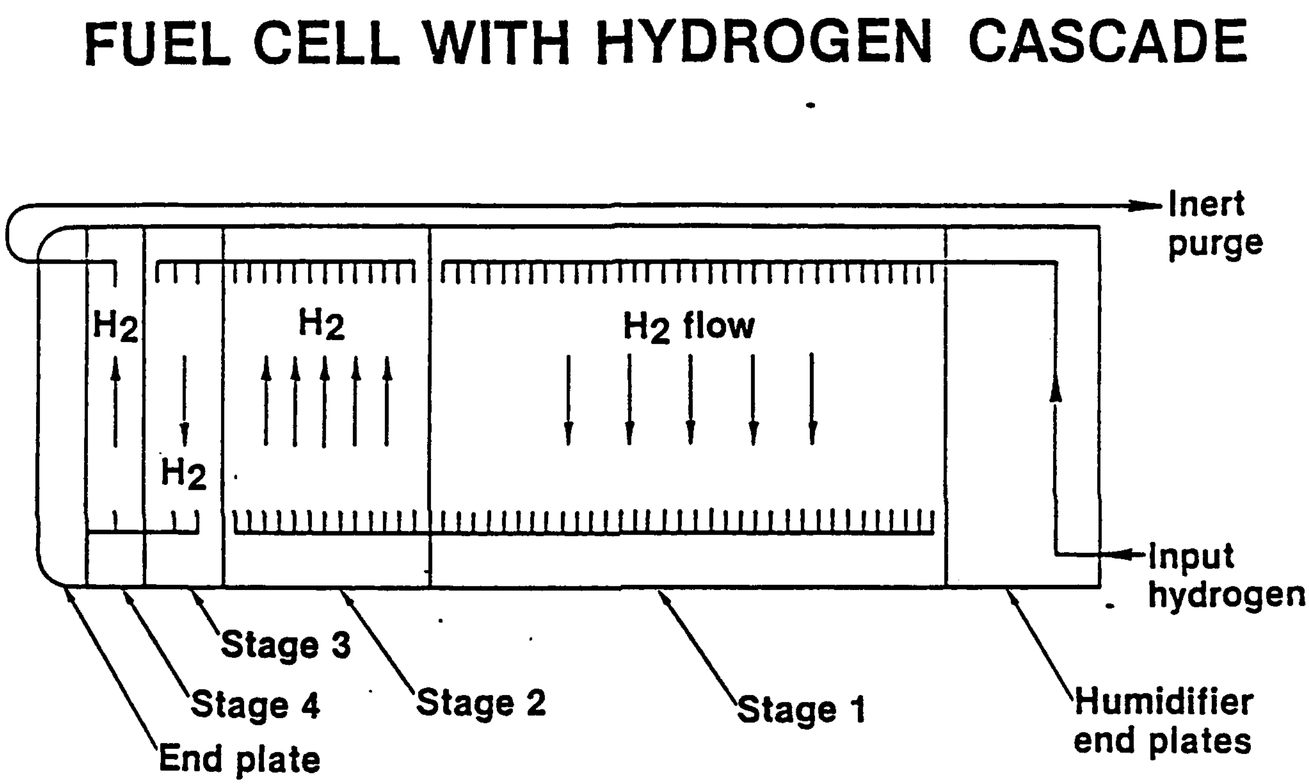


FIGURE 21. Hydrogen Cascade System

The hydrogen subsystem contains a means of storage along with piping for even reactant feed to the module. The hydrogen storage system is charged before the mission through an external fill port. During operation of the module, hydrogen passes from storage through a solenoid valve, a nitrogen referenced regulator and an orifice, before passing through a check valve and entering the fuel cell module. The hydrogen is cascaded through the module such that contaminants will be isolated in a specific block of cells. As the contaminant level builds during operation the performance of these cells deteriorates. The voltage reduction is sensed and a solenoid valve is opened and closed rapidly to flush contamination out of the system. This operation is conducted infrequently during a mission. The hydrogen subsystem components can be protected from the seawater environment by means of a vessel which is pressurized with nitrogen.

7.3 Active Coolant Subsystem

The fuel cell can utilize product water as the coolant fluid. Within the fuel cell the coolant passes through the individual cells in a parallel flow configuration. After absorbing the waste heat of the cells and picking up excess product water, the coolant passes through the reactant prehumidifier which provides the heat of vaporization and the water for humidification. The major components required for the product water coolant subsystem include:

- Coolant Pump
- Stack Temperature Sensor
- Thermal Control Valve
- Heat Exchanger

8.0 REACTANT STORAGE OPTIONS

The SPE fuel cell system makes use of hydrogen gas as the fuel, and oxygen gas as the oxidizer. These gases have the advantage of low cost, ready availability, high energy and freedom from toxic hazards and corrosiveness. Extensive industrial experience with hydrogen and oxygen lends itself to proper storage of these reactants.

8.1 Metal Tankage

Storage of reactant gases in metal tankage is the simplest and most common approach to reactant storage for fuel cells. Gases are most commonly stored at pressures of 3000 psi or less; however, reactant storage at 6000 psi has been successfully achieved in a number of applications.

As the reactant storage pressure is increased, selection of pressure vessel materials becomes a critical issue. At the 3000 psi level or above Inconel 718 is the material of choice for oxygen storage due to the minimal flammability hazard and also compatibility with the fuel cell. For hydrogen storage, AISI 4130 steel or 316 stainless steel are commonly used due to their resistance to hydrogen embrittlement and compatibility with the fuel cell. Commercial tankage can be readily fabricated from these materials for any application.

8.2 Composite Tankage

Pressure vessels fabricated from composite materials have been used in naval and aerospace applications for over twenty years. This reactant storage approach offers significant weight reduction, corrosion resistance and slight volume savings. Composite storage vessels offer the following advantages over metal tanks:

- Higher Specific Strength (Tensile Strength/Density)
- Higher Resistance to Fatigue
- Leak Before Rupture Failure
- Higher Impact Resistance

Cost represents the major disadvantage to utilization of composite tankage. The most commonly used fiber reinforcements for composite tankage are fiberglass, aramid (Kevlar®) and graphite.

Fiberglass - Two grades of fiberglass are available. E-glass is a low cost/low strength material which is commonly used where weight savings of a

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system is not a major factor. The density of composites made with E-glass is 75% that of aluminum. S-glass can be used in applications which require higher strength or stiffness. The strength of S-glass is substantially higher than that of E-glass, and the fiber modulus (a measure of fiber strength) is 20% greater. The cost of S-glass is four times greater than that of E-glass.

Kevlar - In applications requiring high strength and low weight, Kevlar 49, an aramid fiber produced by DuPont, is often used. The tensile strength for Kevlar is only slightly higher than that of S-glass and the fiber density is 40% lower. The cost of Kevlar is approximately twenty times that of E-glass.

Composites which utilize Kevlar as a base material offer better fatigue properties than those which utilize fiberglass. Kevlar composite pressure vessels can be cycled from zero to fifty-five percent of the ultimate pressure over 100,000 times before a fatigue failure occurs while fiberglass/epoxy vessels can only be cycled approximately five-hundred times.

Graphite - A wide range of graphite fibers are available for use in composite tankage with modulus values up to nearly ten times that of E-glass. Prices of the fibers alone can range from fifteen to fifteen-hundred times that of E-glass. These materials are typically used in applications in which low weight and high stiffness are required. Cyclic fatigue properties of graphite composites are, like Kevlar, far superior to those of fiberglass composites.

Composite Pressure Vessel Liners - Due to the inherent porosity of composite vessel shells, composite tanks usually incorporate liners to prevent leakage of the contained fluids. These vessel liners may be fabricated from either metal or elastomers.

Elastomeric Liners - Elastomeric liners are typically either chlorobutyl or actylonitrile rubber and are normally formed around a rigid, water soluble mandrel. This rigid mandrel serves as a base shape around which the composite shell is wound and subsequently cured. The soluble mandrel material is then washed out. Elastomer-lined composite vessels have very high cycle lives and as test vessels have demonstrated in excess of 250,000 cycles to failure. The gas permeability of elastomer-lined vessels is higher than that of metal-lined

vessels. Leakage rates of less than 10^{-7} scc/sec are typical of metal-lined vessels, while rates of 10^{-4} scc/sec are representative of elastomer-lined vessels at a pressure differential of 5000 - 1000 psi when measured in a 2500 inch ^{3} vessel.

Metal Liners - There are two types of metal-lined composite pressure vessels: Those with thin, nonstructural liners, and those with load sharing liners. In vessels with load sharing liners, the liner may carry as much as twenty percent of the load at operating pressure. As the vessel pressure increases, the load is transferred to the composite shell.

The major limitation on the design of metal-lined vessels is cyclic fatigue. The cyclic fatigue capability of the shell far exceeds that of the liner, thereby making the liner design critical to the reliability of the vessel. Table I contains a list of the commonly used metal liner materials. Only the stainless steel and Inconel options are considered for fuel cell applications due to membrane compatibility issues.

TABLE I

METAL LINER MATERIALS

ALUMINUM	TITANIUM
5085-0	6A1-4V (Annealed)
6061-T6	15-3
2219-T6	
6351-T6	**INCONEL**
	INCO-718
STAINLESS STEEL	
321 CRES	**MONEL**
	K-500

8.3 Metal Hydrides

One means of storing hydrogen reactant for the mission is in the form of a metal hydride. This material is simply a metal which contains hydrogen within the interstitial sites of the atomic lattice structure. Most elemental metals will form metal hydrides, however, some perform much better than others in storing hydrogen.

A typical reaction can be written: $M + H_2 = MH_2$

This reaction can proceed in either direction depending on the environmental conditions. If the pressure is above a certain level (characteristic of the material), the reaction proceeds to the right to form the metal hydride; if it is below that level, the metal hydride decomposes to form a high surface area, particulate metal and gaseous hydrogen. Similarly, at an appropriately high temperature, the metal hydride will also decompose.

When gaseous hydrogen contacts a hydride forming metal, hydrogen molecules are absorbed onto the surface of the metal. Some of these molecules dissociate to form atomic hydrogen, which migrates into the crystal lattice of the metal to interstitial sites within the structure. Each crystal structure and base material has a differing size and location of these interstitial sites. As the pressure is increased or the temperature is decreased, the metal becomes saturated with hydrogen and a new hydride phase is formed. Since metal crystals have many of these interstitial sites, large amounts of hydrogen may be stored within the metal. Typically, the number of hydrogen atoms stored in the crystal will be two to three times the number of metal atoms.

The use of a metal hydride for the storage of the hydrogen reactant has many advantages including minimum volume, safety, and the fact that it can be used as a heat sink during discharge. One difficulty with the use of hydrides is the long, relative flat "plateau" in discharge pressure between approximately 10% and 90% of full when using a standard metal hydride. This nearly constant discharge pressure makes it difficult to determine the state of charge based on direct pressure measurement.

Fortunately, hydrides can be modified to produce a slope to the "plateau" for a given temperature. This allows one to prepare a hydride formulation and to know the state of charge by the pressure level at a given temperature combined with the hydrogen flow rate. The state of charge of an SPE fuel cell hydrogen supply can therefore be measurable as the operating pressure ranges as much as 30 psi over the course of the complete discharge.

8.4 Chemical Storage

Chemical storage means may be utilized for oxygen storage within the DAPS system. Fuels such as sodium superoxide can be used if water is available for the reaction. Oxygen is evolved as follows:

$$NaO_2 + 2H_2O \rightarrow O_2 + NaOH$$

Another chemical storage means which has been previously used in buoy power systems is the utilization of sodium chlorate. This reaction:

$$2NaClO_3 \rightarrow 3O_2 + 2NaCl$$

can proceed without exchange of water with the surroundings. Solid sodium chlorate provides an oxygen packing density approximately equivalent to that of liquid oxygen. Chlorate candles are a well established source of oxygen pure enough for breathing purposes. The candles can be pressed into any desired shape and the composition varied to achieve any specified rate of oxygen evolution. These candles are ignited by heating a small area whereupon the reaction proceeds spontaneously to completion.

Hydrogen may be stored in the form of a sodium aluminum hydride ($NaAlH_4$). This compound is readily available and has been used in previous buoy applications. As this solid material is wetted with potassium hydroxide (KOH), hydrogen is evolved. Gas evolution rate may be controlled by regulating the contact area between liquid KOH solution and solid $NaAlH_4$.

8.5 System Recharge

The DAPS power supply may be recharged in a variety of ways depending upon the reactant storage method employed. It is necessary that the gas source pressure be higher than the system storage pressure when gas bottle storage is utilized. The gas source in this case may be commercially available 3000 or 6000 psi gas bottles, may be supplied at lower pressure and compressed to 3000 or 6000 psi, may be generated by applying power to the fuel cell module (regenerative system), or may be generated by means of a stand-alone water electrolysis system. Recharge of cryogenic systems requires a means for chilling hydrogen and/or oxygen for liquefication. Metal hydride canisters may be simply recharged by cooling the hydride canister in the presence of hydrogen allowing the matrix interstices to be replenished. Should the DAPS utilize chemical storage of reactants, these chemicals would need to be replaced after every mission.

Table II summarizes the various recharge options along with the associated technical risk of each. The cost of each recharge option in generally proportional to the technical risk of each.

TABLE II

REACTANT STORAGE	RECHARGE METHOD	TECHNICAL RISK	IMPLEMENTATION COST
3000 psi Gas Bottles	Commercial Cylinders	Low	Low
	Compressor	Moderate	Moderate
	Regenerative	Moderate	Moderate
	Electrolysis System	Low	Moderate
6000 psi Gas Bottles	Commercial Cylinders	Low	Moderate
	Compressor	High	Moderate
	Regenerative	High	Moderate
	Electrolysis System	Moderate	Moderate
Cryogenic Flasks	Liquefication	Moderate	High
Metal Hydride	Canister Cooling	Moderate	High
Chemical	Replacement	Low	High (Replacement Cost)

9.0 ELECTRICAL SYSTEM REQUIREMENTS

The control module provides the primary control for the SPE power system. Because the fuel cell is a self-regulating device, control requirements are minimal. Under normal operation the controller receives inputs from the various sensors and the control and signal interface. These inputs are processed to control operation of the unit to provide the following functions:

- Start/Stop Sequencing
- Automatic Hydrogen Purge Control
- Coolant Control
- Sensing of Overvoltage and Undervoltage Conditions
- Cell Diluent Control

Under normal conditions the fuel cell power system will be automatically shutdown for:

- Over Temperature
- Low Oxygen to Hydrogen ΔP
- High Oxygen Pressure
- High Hydrogen Pressure

Inputs to the control module would include the following:

- Module Temperature
- Fuel Cell Terminal Voltage
- Hydrogen Pressure (Inlet Transducer)
- Oxygen Pressure (Inlet Transducer)
- Pressure Differential Transducer (Oxygen to Hydrogen)
- Start Switch

Figure 22 shows a typical system control block diagram.

Various system control schemes can be considered for the fuel cell. Factors considered in the evaluation included reliability, versatility, size, weight and cost.

10.0 POWER CONDITIONING EQUIPMENT

The SPE hydrogen/oxygen fuel cell normally produces clean D.C. power. In order to meet the power requirements of the DAPS, this power must be modified such that alternating current is produced. This may be achieved via utilization of an inverter, or by rapid switching of a fuel cell to produce an A.C. output.

10.1 Inverters

The SPE hydrogen/oxygen fuel cell produces a highly invariant level of D.C. power. As current is drawn from the fuel cell power system, the module voltage drops from the open circuit value down to the operating level. This level is based on a current/voltage relationship which is characteristic of the hydrogen/oxygen fuel cell and is known as a polarization curve.

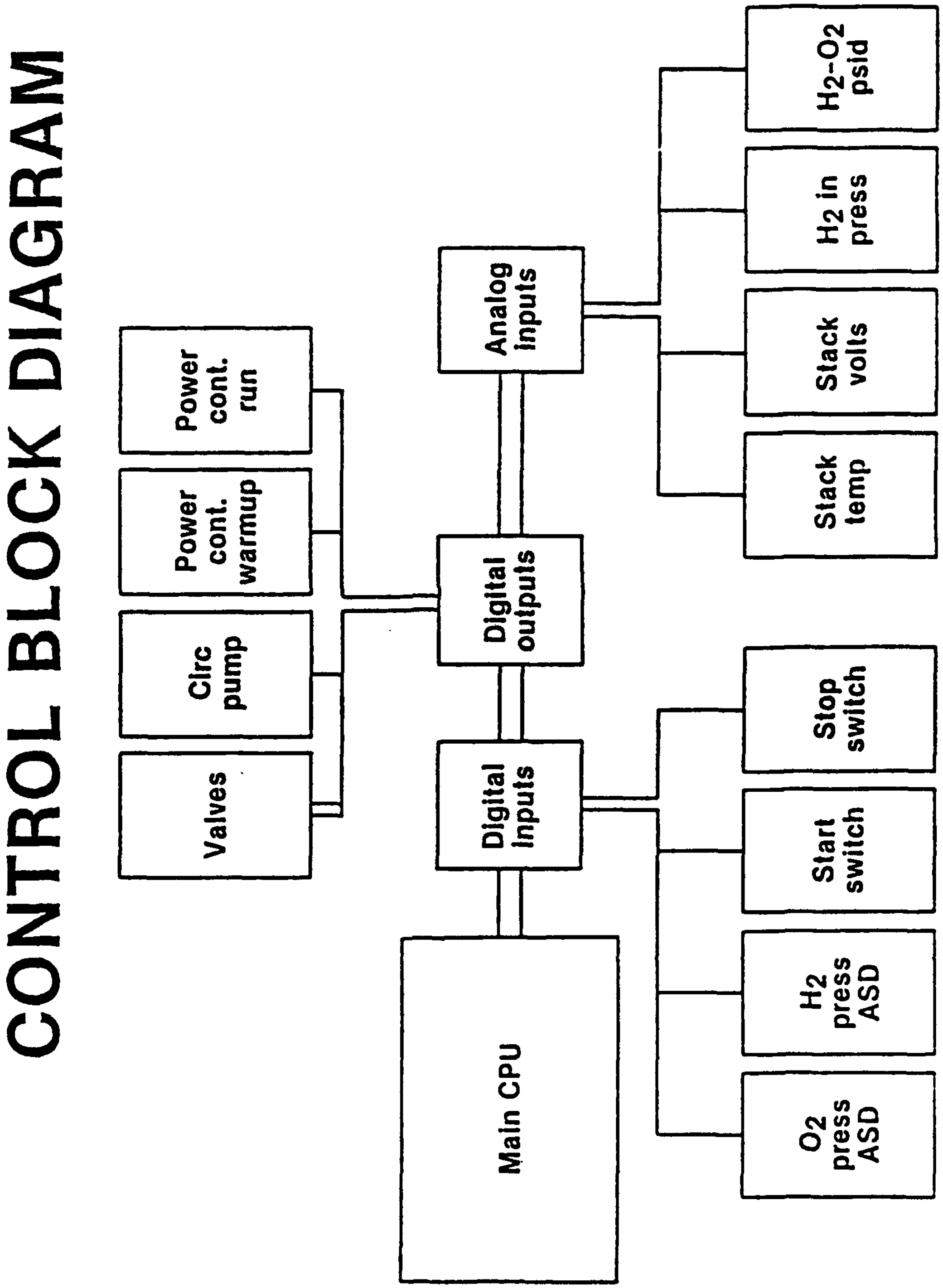

FIGURE 22. Control Block Diagram

It is necessary to convert the D.C. power produced by the fuel cell to A.C. in order to power the DAPS. This may be achieved by means of a high power inverter. By using an inverter, a reliable A.C. power output may be derived from the hydrogen/oxygen fuel cell for the pulse application.

A block diagram for a typical inverter is shown in Figure 23. This inverter consists of the following elements:

- Wein Bridge Oscillator with Zener Diode Regulation
- Pre-amplifier
- Push-pull Class AB Power Amplifier
- Interconnecting Feedback Circuits

Although not all inverters are alike, most utilize these basic components.

From a D.C. input, the oscillator generates an A.C. signal which is regulated and stabilized to compensate for supply voltage variations. The signal is coupled to a pre-amplifier which raises the power to a level compatible with the power amplifier input. The A.C. signal is smoothed with the push-pull power amplifier and the power is raised to the output level. Feedback paths exist from each amplifier to assure constant output voltage stability.

There are many inverter manufacturers in industry. Although many inverters are available as off-the-shelf items, it will likely be necessary to modify existing technology to accommodate the requirements of the DAPS program. Since few stock items are capable of delivering the necessary power level. Factors to be considered include:

- Volume
- Weight
- Cost
- Reliability
- Duty cycle
- Power output requirements

Of the manufacturers contacted, many had experience in producing Navy certified hardware.

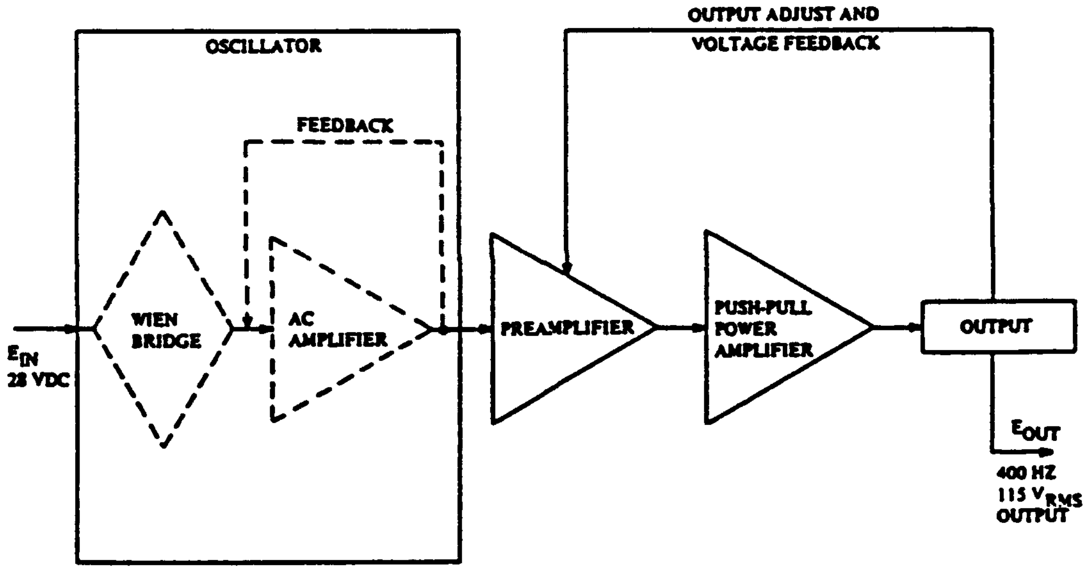

FIGURE 23. Inverter Block Diagram

It appears that off-the-shelf industrial quality inverters would be moderately heavy and bulky since they are sized to meet long term steady state power demands. One such unit measures 19" x 24" x 72" and weighs 3000 - 4000 pounds. This unit relies on free convection to the outside environment for cooling. Much of the weight and volume of the unit may be attributed to this self cooling mechanism. It is expected that the size and weight of a unit designed specifically for this application could be less than half that of the catalog item. Off-the-shelf inverters cost from $100K - $200K , while a fully developed prototype unit should cost slightly more.

10.2 Inverterless Systems

Hamilton Standard IR&D studies have shown that the SPE fuel cell can be adapted to produce alternating current directly. In this manner, much of the heavy and voluminous power conditioning equipment can be eliminated, thereby increasing total system power density. Implementation of this concept would also significantly reduce the cost of the system package. Although some work in this area is necessary for verification of details, the benefits of the A.C. output fuel cell for the DAPS are formidable.

11.0 POWER SYSTEM SAFETY/RELIABILITY

Over the past thirty years there has been a constant approach used to provide a "man-rated" system safety in SPE fuel cells. That approach incorporates:

- Oxygen Overpressure
- Minimum Fuel Volumes
- Careful Materials Selection
- Fault Detection and Automatic Shutdown
- Positive Separation of Fuel and Oxidant

The concern for safety is the central driver defining the configuration of the fuel cell. The same safety issues inherent in the design of and operation of hydrogen/oxygen fuel cells have been addressed in the design of the U.S. Navy OGP high pressure electrolysis system where safe operation at 3000 psi has been demonstrated. The criterion used to evaluate the inherent safety of the system is that no two credible failures presents a personnel hazard.

The specific safety issues associated with the fuel cell are described in the paragraphs that follow together with safety provisions included in the power system design. Provisions include the use of sensors, safety shutdown/purge procedures, redundant valves, pressure vessels, solid polymer electrolyte membrane, nitrogen reference pressure and oxygen over hydrogen pressure control.

The motivation for pursuing the SPE fuel cell approach is the inherent high reliability and safety which result from the simplicity of the design. The SPE fuel cell is both simple and lightweight, requires few ancillary components for operation and control, is easy to place on-line and to shutdown, does not require close control of anode/cathode chamber pressure differentials, is not affected by small quantities of carbon bearing gases within the reactants and is not subject to dilution of the electrolyte in operation. It also has the capability to meet high levels of environmental stresses such as vibration, shock and acceleration.

11.1 Safety considerations

The processing of hazardous gases, and in particular oxygen and hydrogen at elevated pressures, present potential safety hazards. These hazards result from three possible sources:

1. High pressure oxygen combustion;
2. An internal detonation which results in the release of fragments beyond the system packing envelope;
3. An external hydrogen leak.

11.1.1 Oxygen Combustion

The need to contain the effects of high pressure oxygen combustion dictates that the sources of the hazard be tightly controlled. There are two potential hazard sources; the first results from material compatibility and cleanliness, the second from the introduction of hydrogen into the oxygen circuit.

The first hazard is minimized through adherence to well defined Hamilton Standard design standards for oxygen equipment. Design features addressed in the standard include material selection and control, seal configuration, cleanliness and filtration requirements, electrical grounding and drawing details such as edge break and radii. Hamilton Standard has extensive experience with the design of flight qualified oxygen systems including the 6000 psi Space Shuttle Extravehicular Mobility Unit oxygen system.

Exposure of the low pressure oxygen circuit to high pressure oxygen is prevented by two overpressure protection functions. Two different and independent pressure relief technologies have been incorporated; one pneumatic, the other electrical. Pneumatic relief is provided by a backpressure regulator installed in the low pressure circuit. Back-up pressure relief is provided by the controller by monitoring the oxygen pressure and the oxygen/nitrogen differential pressure. If either sensor exceeds specified limits, a low pressure oxygen vent valve is opened and the redundant oxygen inlet supply valves are closed. During quiescent periods when the oxygen source is pressurized and the controller is off (or failed off), the redundant oxygen supply valves will automatically close. In the event that both supply valves leak, pressure relief would still be provided by the backpressure regulator valve.

The second source of oxygen combustion results from the possible introduction of hydrogen into the oxygen circuit. This is minimized by limiting the single barrier oxygen/hydrogen interface to the fuel cell and by maintaining the oxygen pressure above hydrogen to control the direction of cross leakage within the cell. The cell membrane has been demonstrated to withstand differential pressure of greater than 700 psi. The nominal oxygen operating pressure is 100 psia and the hydrogen pressure is maintained 25 psid below the oxygen pressure. In the baseline design, there is sufficient redundancy incorporated within the pressure regulation and relief valves so that no two failures produce a differential pressure greater than 200 psi and that no single failure results in a pressure reversal of hydrogen above oxygen. Thus, the SPE fuel cell design has a 3.5 x factor of safety with two credible failures.

To accomplish this, a pressure hierarchy was developed so that in the event of a leakage at a two gas interface the direction and effect of the leakage is known. Nitrogen within the fuel cell enclosure is maintained at the highest pressure. Oxygen pressure is maintained 50 psid below that of nitrogen, and hydrogen pressure 25 psid below that of oxygen. This is to insure that leakage at an oxygen/hydrogen interface within the fuel cell module results in oxygen leakage into the hydrogen system. In the event of a loss or drop in the oxygen supply pressure, nitrogen is introduced into the oxygen circuit via a nitrogen relief valve to maintain the oxygen pressure circuit above hydrogen pressure. The hydrogen pressure is maintained below the oxygen pressure through the backpressure regulator referenced to the nitrogen.

Because of the possibility of introducing hydrogen into the oxygen circuit through the nitrogen reference and purge line following two failures, the nitrogen reference lines to the oxygen and hydrogen circuits are isolated through the nitrogen pressure dome enclosing the fuel cell. The intermediate nitrogen volume is used to reduce the hydrogen concentration below one percent following two failures before its introduction into the oxygen circuit during a failure depressurization sequence.

11.1.2 Internal Detonation

The components in the oxygen circuit do not have to be designed to contain an explosion, since more than two failures are required to introduce an explosive mixture. An explosive mixture, although highly unlikely, could be introduced in the hydrogen circuit as a result of internal cross leakage in the cell.

If an internal cross cell leak developed, the effects would be minimal; oxygen gas will flow into the hydrogen subsystem and react with the hydrogen gas in the presence of platinum catalyst. Since the hydrogen side volume is designed to contain a minimum quantity of gas, the hydrogen fuel is consumed and the hydrogen flow automatically stopped by the oxygen overpressure checking of the hydrogen input.

Experience has shown that the above sequence occurs without creating a safety hazard. By limiting the fuel, including construction materials, damage is maintained very locally. Over the years, a number of demonstrations have been conducted in an attempt to cause detonation without success.

The components in the low pressure hydrogen circuit and the low pressure oxygen circuit are installed within the fuel cell nitrogen enclosure. The nitrogen enclosure is designed to contain the fragments following a detonation in the low pressure hydrogen circuit. The oxygen component within the enclosure is isolated from the hydrogen components by a barrier so that fragments released from an explosion in the hydrogen circuit cannot damage a low pressure oxygen component.

The hydrogen components within the enclosure are designed for the maximum overpressure capability achievable within practical design limits. As a goal, they should be designed to contain an internal deflagration.

11.1.3 External Hydrogen Leak

The impact of an external hydrogen leak is related to the location of the hydrogen components within the fuel cell system. Hydrogen components installed within the pressurized nitrogen enclosure have no external leakage paths. The nitrogen within the enclosure is the system pressure control reference. The hydrogen circuit pressure is maintained through a backpressure regulator at a pressure level below the reference nitrogen. Any external leakage path at a hydrogen component will result in leakage of nitrogen into the hydrogen circuit, a drop in nitrogen pressure and a decrease in the system pressure and performance at a rate corresponding to the leak. This would be detected by the subsystem pressure sensors, the fuel cell voltage and current sensors, and a shutdown purge initiated.

11.2 Fault Detection and Automatic Shutdown

The controller monitors the operation of the fuel cell using the following sensor data; oxygen, hydrogen and nitrogen tank pressures, regulated oxygen

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and hydrogen pressure, regulated oxygen/nitrogen and hydrogen/nitrogen differential pressure, fuel cell current and voltage, water tank level and the coolant loop temperature and flow. In the event an out of tolerance condition is measured, an emergency shutdown of the fuel cell system is executed.

The controller also monitors its own "self-health" through a series of software and signal conditioning tests. A failure of the controller to issue the proper refresh signal to two redundant watchdog timers results in power removal to the controller and the system.

Shutdown of the fuel cell is executed in one manner: Power removal to the fuel cell, pump and solenoid valves. Redundant hydrogen and oxygen supply valves close, isolating the high pressure tanks. The hydrogen purge valves and the nitrogen to hydrogen purge valve open, purging the low pressure hydrogen circuit with nitrogen. The drop in nitrogen pressure causes the oxygen backpressure regulator to open, depressurizing the oxygen circuit.

11.3 General Safety Considerations

Care must be exercised in developing and operating systems which utilize hydrogen and oxygen gases at elevated pressure. Hamilton Standard has developed a set of guidelines which ensure safe construction and operation of electrochemical energy conversion systems which utilize hydrogen and oxygen. These hydrogen and oxygen guidelines exceed safety standards set forth in Military Specifications and NASA regulations. Particular emphasis is placed on component design, materials compatibility, gas handling and storage. Utilization of guidelines such as these is necessary in order to avoid the creation of hazardous situations during fuel cell power system operation, recharge and shutdown.

11.4 Power System Reliability

A summary of the component failure rates used in this study is presented in the table on the following page. The failure rate of the fuel cell module is based on 5.5 million cell hours of fuel cell testing, during which two fail-

DAPS SYSTEM RELIABILITY PREDICTION

SUBASSEMBLY/COMPONENT	FAILURE RATE x 10^{6}	NUMBER USED	COMPONENT FAILURE RATE	ASSEMBLY FAILURE RATE	MTBF (HOURS)
1. Fuel Cell Assembly				60.557×10^{-6}	16,528
Fuel Cell	0.36	160	57.60		
Humidifier	0.36	2	0.72		
End Plates	1.00	2	2.00		
Pressure Vessel	0.237	1	0.237		
2. Pressure Control Assembly				40.248×10^{-6}	24,846
Solenoid Valves	1.64	8	13.12		
Relief Valve	1.586	4	6.344		
Check Valve	1.59	4	6.36		
Manual Valve	0.175	5	0.875		
Pressure Regulators	2.435	2	4.87		
Backpressure Regulators	2.435	3	7.305		
Flow Restriction	0.3	3	0.9		
Pressure Vessel	0.237	2	0.474		
3. Temperature Control				19.39×10^{-6}	51,573
Storage Tank	0.237	1	0.237		
Heat Exchanger	0.904	1	0.904		
Liquid Level Sensor	2.156	1	2.156		
Water Pumps	12.013	1	12.013		
Temperature Control Valve	4.08	1	4.08		
4. Control and Instrumentation				65.652×10^{-6}	15,257
Controller	25.0	1	25.0		
Pressure Sensor	6.757	6	40.542		
			TOTAL	185.847	5382 Hours

ures were encountered which were categorized as random (i.e., within design life and not detectable or not correctable within practical means). From that experience, a failure rate of 0.36 x 10^{-6} failures/hour was established for individual cells. The failure rates for the remainder of the components were obtained from NPRD-2, Nonelectric Parts Reliability Data, RADC, using ground fixed as the operating environment.

12.0 TECHNOLOGY ASSESSMENT

Little development effort is required to adapt existing SPE fuel cell technology to meet power requirements of the DAPS. The basic cell hardware (membrane and electrode assembly) is firmly established for the DAPS power system. This basic building block has been successfully evaluated for millions of cell hours under conditions more severe than those discussed herein.

The primary consideration for the power system is the general fuel cell mechanical configuration. The fuel cell power plant, excluding the fuel storage, consists of several components, all dependent upon the peak power level and the duty cycle. The largest and most important component is the cell stack itself, which contains the individual cells where electrolytic combination of hydrogen and oxygen is performed. The area of the cells is made of both active and inactive components, while the cell stack also includes end-plates (which contain the internal pressure) and spring-loaded tie rods (which bind the assembly together). The current density determines the stack size and weight for fixed cell sizes. The size of the other ancillary components are a function of power output and duty cycle.

12.1 Physical Dimensions

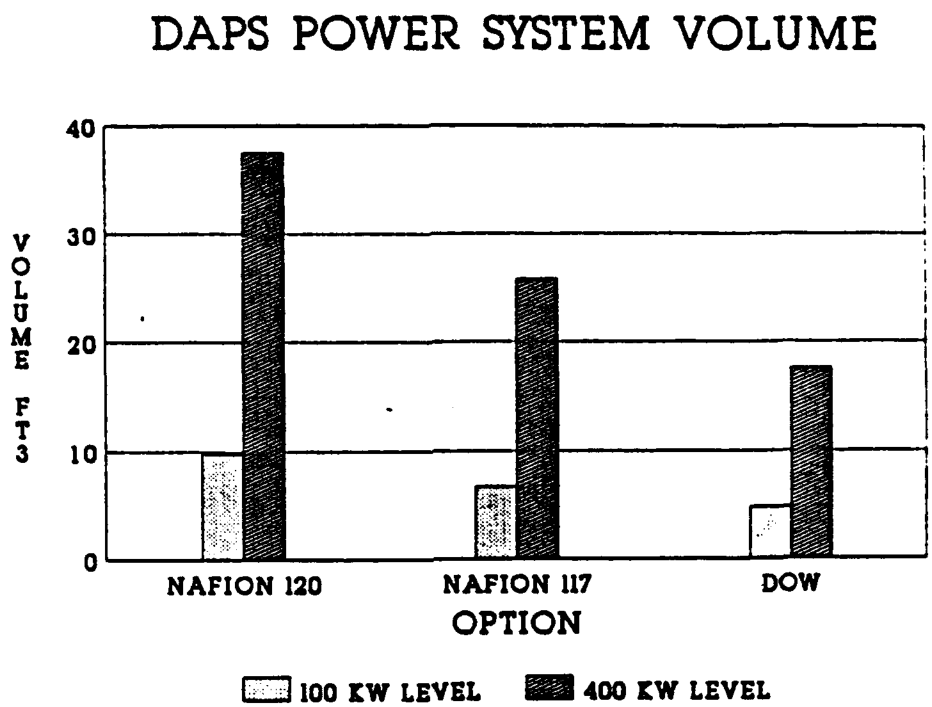
The state-of-the-art fuel cell design which has been constructed and operated for both electrolytic gas generators and fuel cells normally uses three separate chambers per cell. Each chamber contains its own screen for fluid and electrical current distribution and its own support frame and manifold. The thickness of the entire combination is about 0.22 inch. This 0.22 inch dimension becomes an important factor in determining the total space required

for a fuel cell with a fixed active surface area. A second important factor is the amount of cell surface area used for the fluid ports and the tie rod supports. One fuel cell design contains a twelve inch diameter active surface area while the outer diameter of its containment vessel is sixteen inches. Similarly, if a twenty-one inch vessel diameter is allowed (compatible with torpedo handling systems), the anticipated diameter of the active area would be approximately sixteen inches. The third factor in computing the volume of the power plant is the space required for storage of the ancillary components. Some components, such as the fuel cell stack and end plates are dependent mostly upon the number of stacks in the power supply, a number which is in turn proportional to the number of cells (and the total cell volume). Other components, such as the cooling water pump, vary mostly with the power level, not necessarily with the number of cells. Structural components typically add about 50% more volume to the cell stack. Additional components occupy about 1 $Ft.^3$ for each 50 kW power capacity and include the coolant circulation pump and heat exchanger. These three dimensional assumptions all stem from selection of the three-screen cell design. Figure 24 shows the approximate module/system weight and volume for three separate configurations.

12.2 Membrane Performance Characteristics

The performance characteristics of the fuel cell depend largely upon the electrolytic membrane used. Three solid polymer membranes are considered, each possessing unique polarization characteristics. Membrane selection involves a trade-off between reliability/durability and performance capabilities. Two of the membranes are manufactured by DuPont; Nafion 120 and Nafion 117. The third membrane is produced by Dow Chemical. The polymer structure of each is depicted in Figure 25. The Nafion material owes much of its improved mechanical strength to the physical entanglement caused by the longer polymer side chains. The Dow material contains more active sulfonic acid groups (SO3H) per unit weight, thereby making it more ionically conductive, and therefore a higher performance material. However, the lower mechanical strength of this material may influence the useful life.

Fuel cells and electrolyzers configured with Nafion 120 represent mature technologies, based on over 90,000 hours of satisfactory cell performance on electrolyzers and 60,000 hours on fuel cells demonstrated in the laboratory.



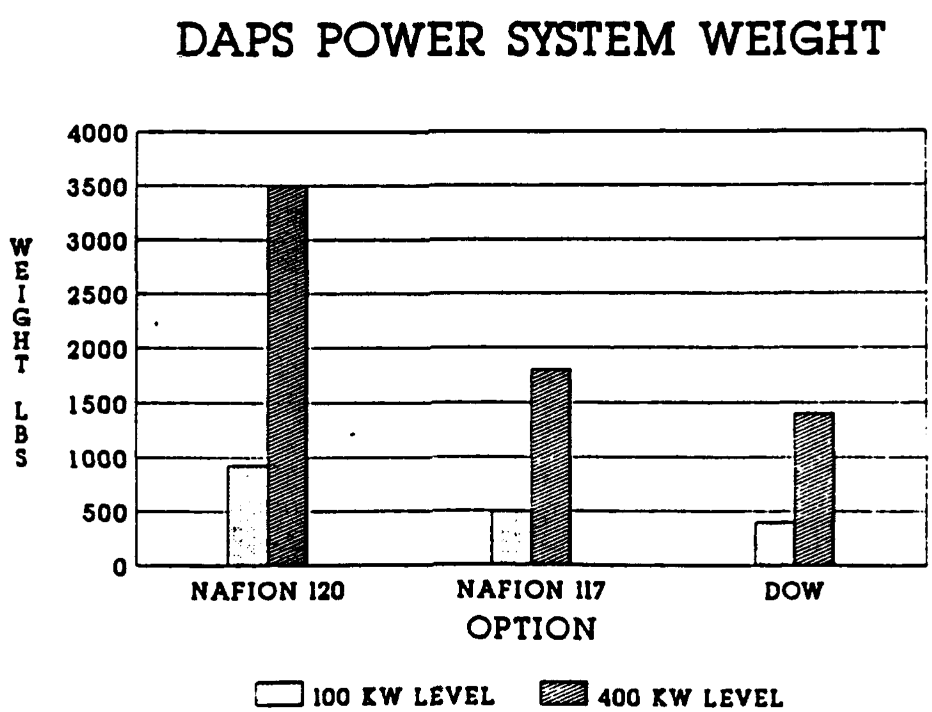
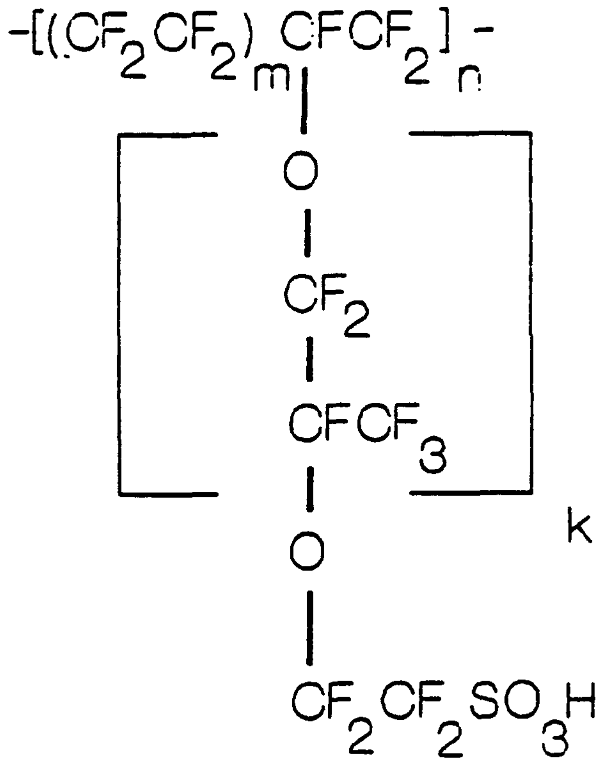


FIGURE 24. Estimated Module Volume/Weight

PERFLUOROCARBON ION EXCHANGE MEMBRANES



DUPONT NAFION: k>0, DOW: k=0

FIGURE 25. Membrane Polymer Structure

The membrane is durable and has exhibited strong resistance to degradation. Nafion 117 is a high performance membrane, with a more recent development history and several thousand hours of laboratory operation. Figure 26 shows the expected performance of cells configured from each membrane. The higher voltage of Nafion 117 and Dow membrane allows a greater energy density or a smaller cell stack for the same power requirements. Fuel efficiency is also improved. The Dow membrane is the most recently developed and possesses the highest performance and the lower physical strength. Dow offers a continuum of ion exchange membrane materials, all in limited production. The Dow membrane can be operated at up to 3900 ASF, well above the 750-1500 ASF limit of the Nafion membranes. At lower current densities the Dow membrane has a higher voltage than either Nafion membrane (Figure 26). However, the feasibility of long term operation of Dow membrane has yet to be proven.

12.3 Transient Performance

A solid polymer electrolyte fuel cell is particularly well suited for high power pulse applications because of the large equivalent capacitance usually associated with the electrode - electrolyte combination. Along with this capacitance, the equivalent electrical circuit contains an ohmic component associated with the electrolyte and current collection hardware and also an impedance associated with the chain of electrochemical reaction steps which take place at each electrode. A representative circuit is shown in Figure 27.

Fuel cell transient response is a function of: Cell component type and geometry, operating conditions, pulse amplitude, frequency and duration. During steady state operation, most of the contribution of cell capacitance is lost. Figure 28 compares pulse performance with steady state performance. This Figure emphasizes the advantages of transient cell operation.

13.0 SYSTEM TRADE-OFF STUDIES

The projected material costs of the fuel cell power supply and the fuel storage can be determined in a similar manner to that of the total weight and total volume, provided that reasonable assumptions can be made on the relative costs of each type of power supply. However, the basic rules relating material cost to fuel cell active area or to fuel storage units are affected by

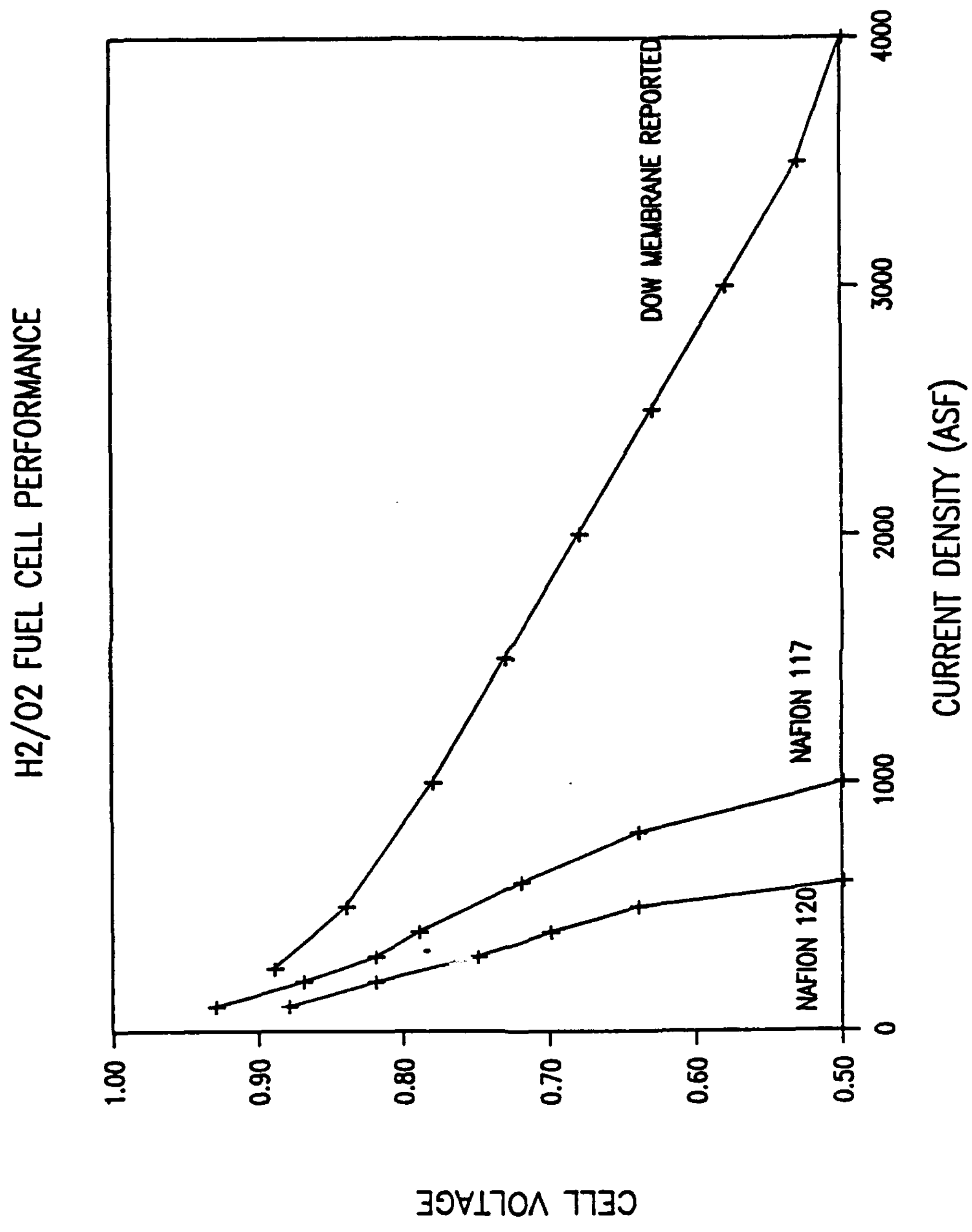
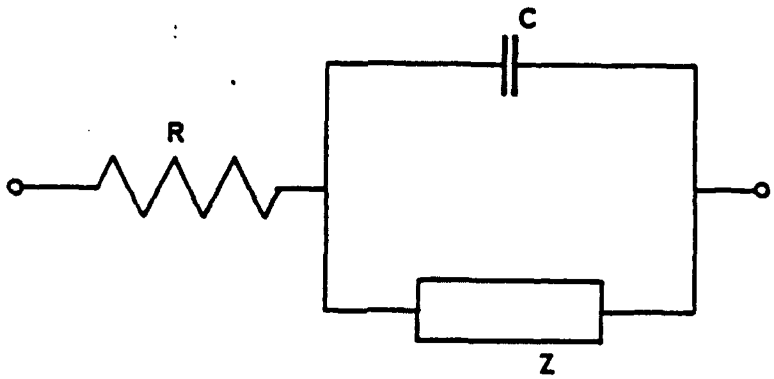


FIGURE 26. Expected Cell Performance



R = Ohmic Resistance - Electrolyte

C = Cell Capacitance - Electrodes/Double Layer

Z - Faradaic Impedance

FIGURE 27. Representative Equivalent Circuit

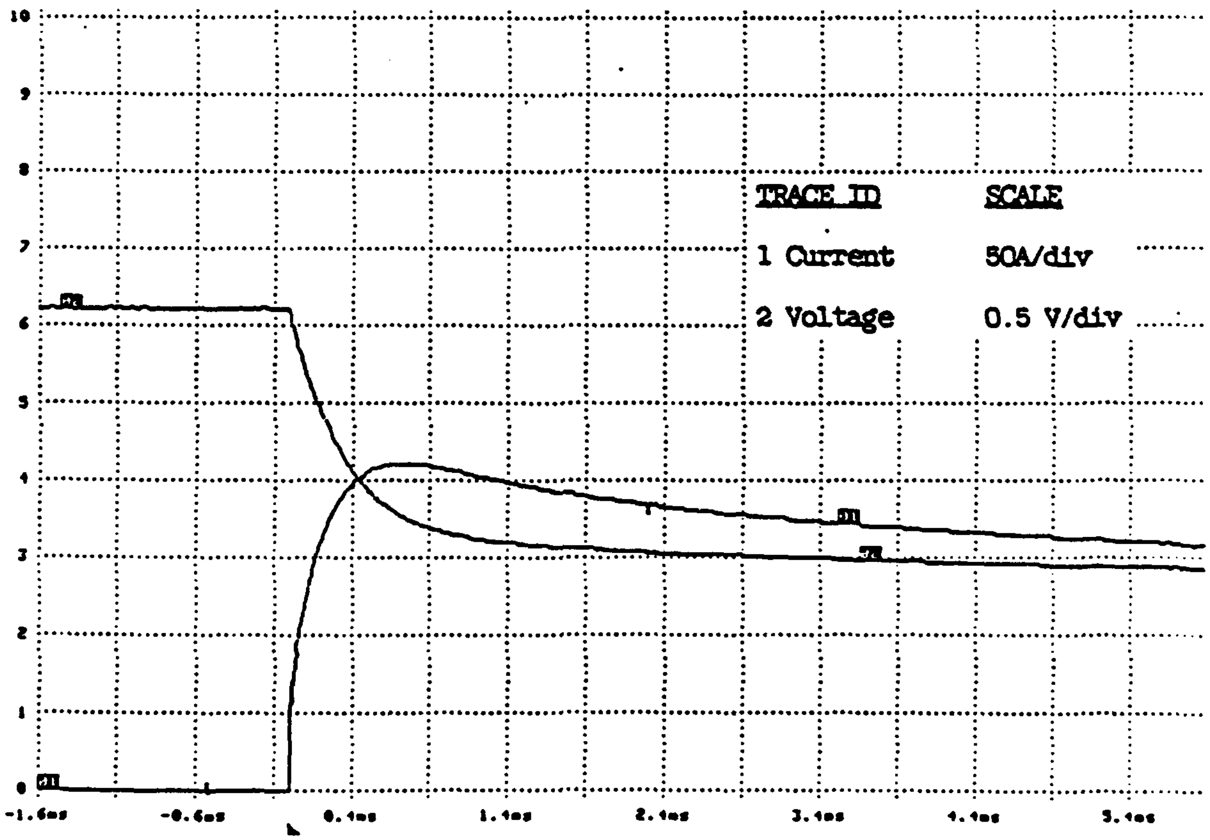


FIGURE 28. Fuel Cell Pulse Performance

availability, the choice of supplier and the size of the order lot. It is also difficult to accurately compare the costs of those items manufactured in-house and those purchased fully assembled from the supplier. For the purpose of this study, the material costs will include parts and labor required to assemble the complete fuel cell power supply. Purchase costs for storage containers will reflect their direct price from the supplier. In general, cost information is difficult to obtain from suppliers without a formal request, but estimates will be based on catalogue information, verbal and written sales quotes and prior contracts. Figure 29 shows the anticipated module cost for several options.

13.1 Reactant Storage Trades

Several basic generalizations may be used in estimating the volume, weight and cost of the various reactant storage schemes. It can be assumed that the value of each of these parameters is directly proportional to the weight of the particular reactant stored. Based on these generalizations estimates of reactant storage volumes, weights and costs for these options may be generated. These data are presented in Figures 30, 31 and 32. Most of these numbers have been generated based on vendor supplied information.

Of the six options presented for hydrogen storage, the utilization of commercially available tankage for storing 3000 psi hydrogen represents the lowest technical risk option. The penalty paid for implementing this option is that a relatively high system weight and volume is necessary. Storage of hydrogen at 6000 psi in commercially available vessels is also a low technical risk option and offers significant weight and volume savings. Metal hydrides offer significant volume savings at a higher cost and weight. Although chemical storage means have been previously used in buoy applications, recharge of the system may prove difficult and costly. Utilization of cryogenic hydrogen can be expensive and difficult to implement - especially when system recharge is considered. Storage of hydrogen in composite vessels offers various benefits in storage weight and/or volume, and can be achieved at moderate cost.

Five options are presented for storage of oxygen. Stora oxygen in 3000 psi Inconel vessels is the conventional, but most minous option.

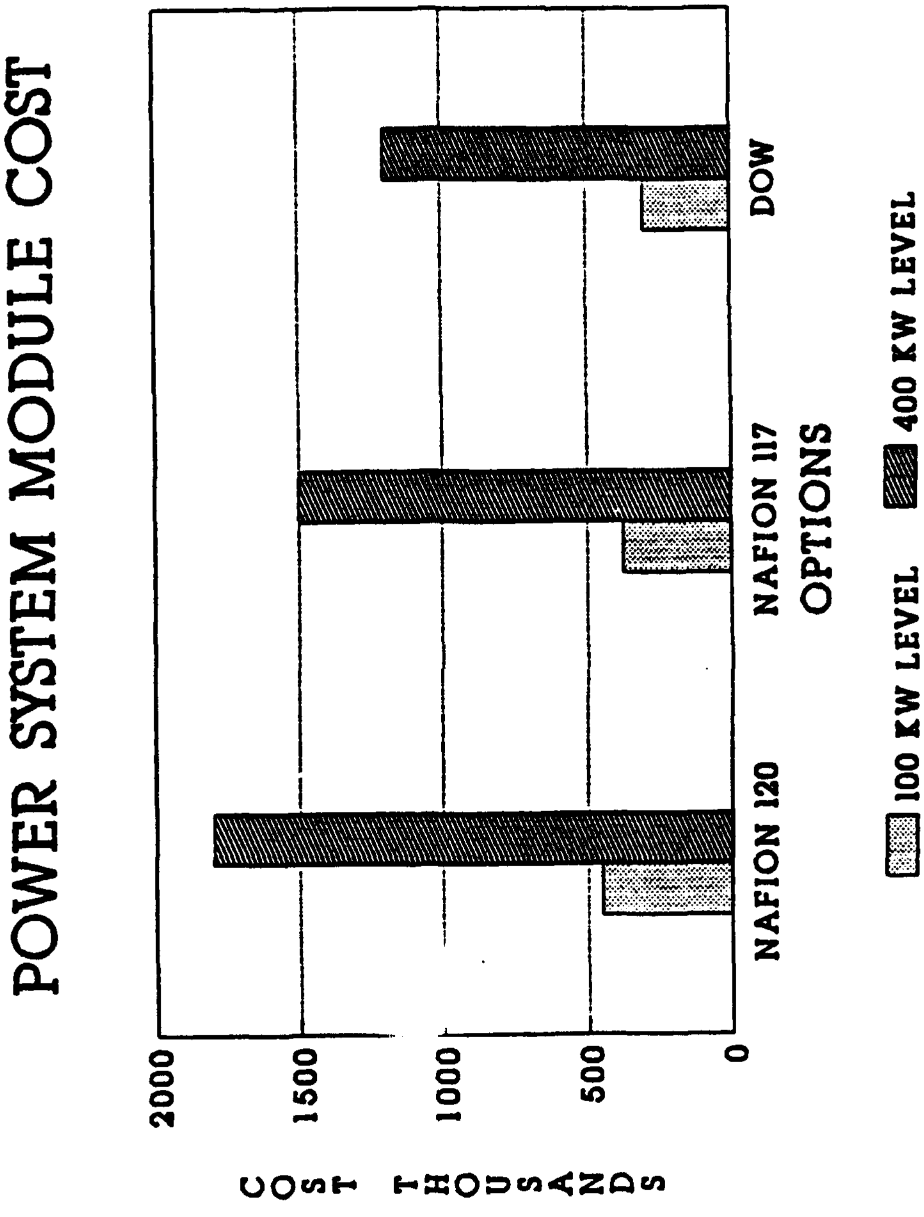


FIGURE 29. Anticipated Module Cost

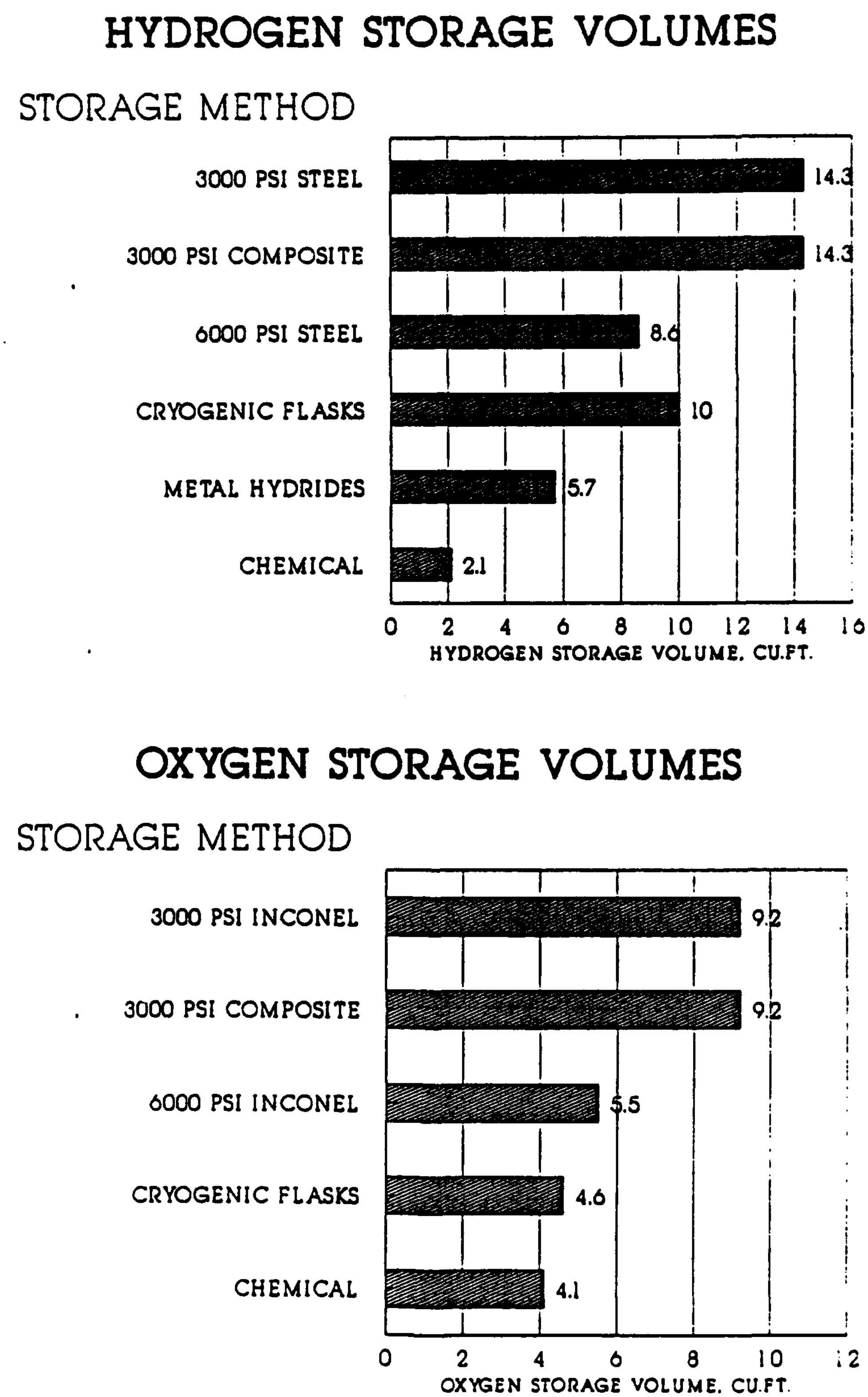
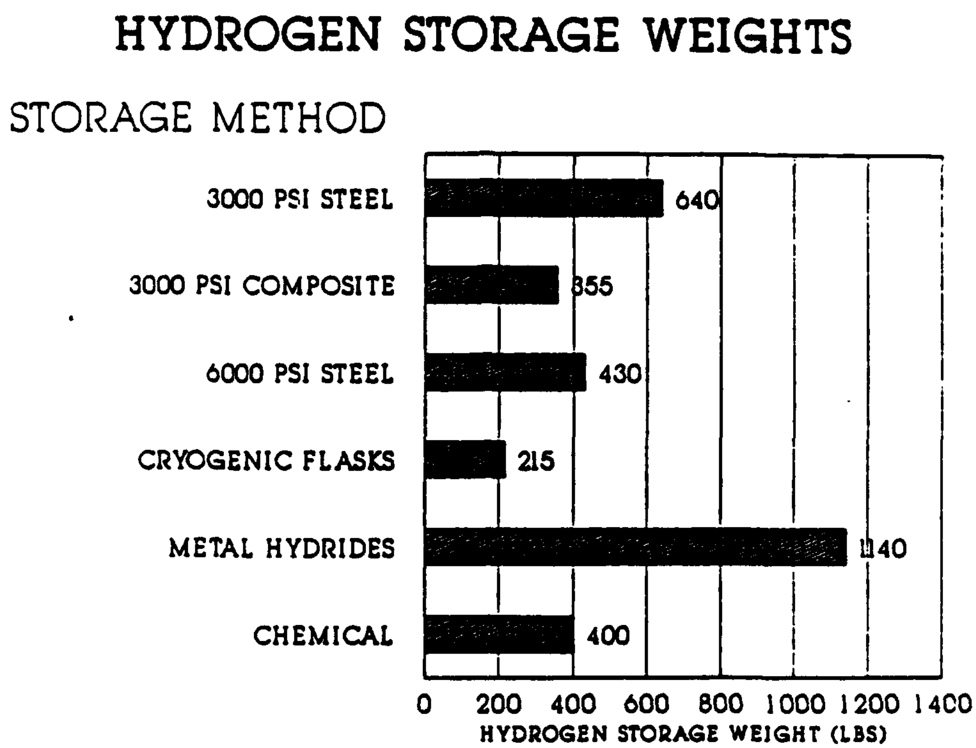


FIGURE 30. Reactant Storage Volume



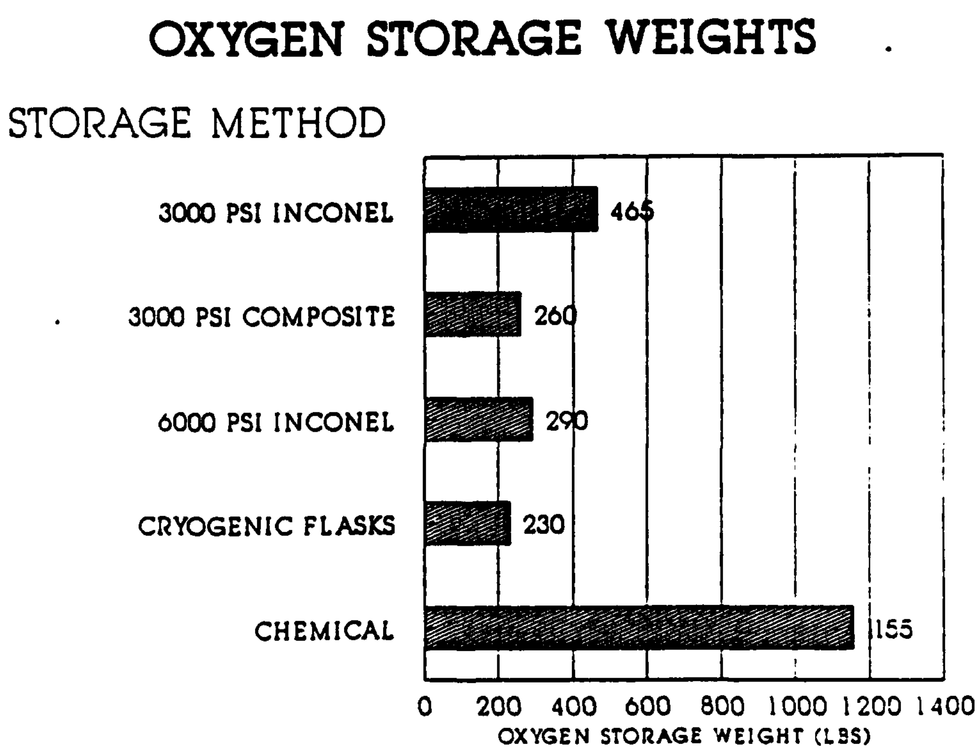
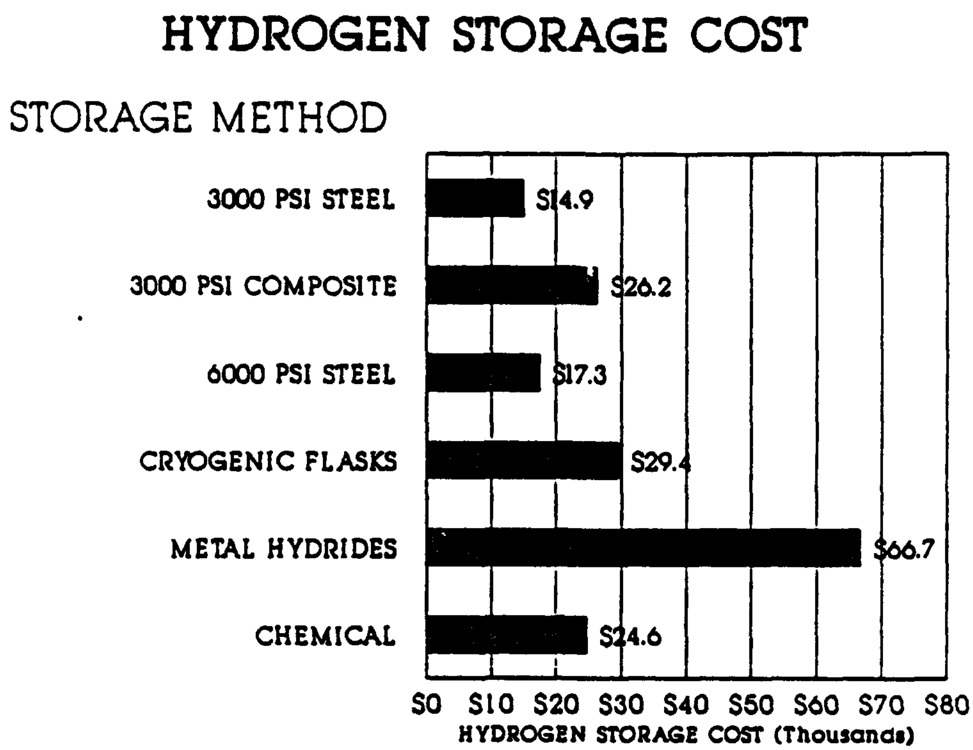


FIGURE 31. Reactant Storage Weight



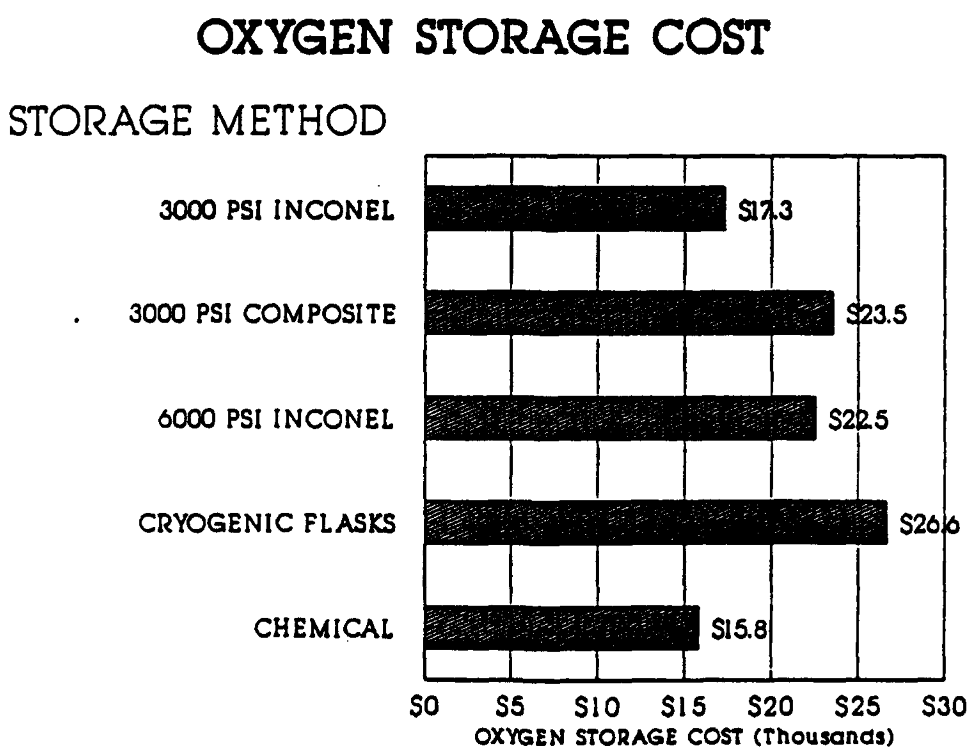


FIGURE 32. Reactant Storage Cost

Significant volume savings may be obtained through the utilization of cryogenic or chemical storage techniques, however, recharge is difficult in both cases. Storage in 3000 psi composite vessels and also in 6000 psi Inconel vessels represent only slightly higher technical risk options than does the conventional method, but with higher volume and/or weight advantages.

13.2 System Recharge

The method of system recharge employed can be dependent on the reactant storage scheme employed. The quality of gas produced in all cases must be quite pure in order to minimize cell contamination or electrode masking. Electrolytically generated gases are often used for fuel cell applications due to their inherent high purity.

One mode of system recharge involves the implementation of a regenerative fuel cell system. In this option, after the reactant gases have been consumed, a potential is applied to the fuel cell modules such that water is electrochemically decomposed to form hydrogen and oxygen gases. In this mode, water must be fed to either the anode or cathode chamber of each cell. Recharge can be attained in approximately the same number of load hours that the fuel cell experiences during a mission.

A second means of system recharge is to simply provide bottled gas to the reactant storage tanks, hydride, etc. This method, although simple, can be somewhat costly and may also provide significant logistics problems.

A third means of system recharge is to provide a stand alone water electrolysis system for gas generation. This allows the convenience of being able to move the regeneration unit to the deployment vehicle. If multiple recharges are required, this option would likely be most cost effective.

If cryogenic reactant storage means are employed, a means of reactant liquefication must be utilized. This can be quite complex and costly, and may also be inconvenient if the system is to be recharged aboard ship.

Chemical reactant storage means must be recharged by replacement of the chemical canisters in the system. Although the system may be designed to facilitate this operation, frequent replacement of these chemicals is quite expensive.

14.0 SUMMARY

Results of this study indicate that viable options can be produced which utilize each membrane type (Nafion 120, Nafion 117 and Dow) to achieve the power levels required for the DAPS application. This is further defined in Table III. Here, twelve design options are presented with differing membranes, cell hardware sizes, or number of modules bussed in parallel. Each option utilizes circular screen type hardware similar in design to that presently being utilized in nuclear submarines for life support. The viable options presented in this Table contain either one or two modules, each comprised of approximately 500 cells. This design assumes that the 400 kW peak power requirement is attained at a current output of 1000 amperes. If the current level is increased, then the number of cells required for the DAPS may be significantly reduced.

Both steady state and pulsed power performance characteristics have been demonstrated in solid polymer electrolyte fuel cells such that the performance requirements of the DAPS could be easily met. Furthermore, fuel cell hardware which would be necessary for the DAPS is either presently in use or represents a slight modification of production cell hardware. This hardware has successfully demonstrated more than 90,000 hours of highly invariant performance in the laboratory. Systems safety criteria have been established and demonstrated in SPE cells such that safe operation is guaranteed.

Reactant storage represents the largest contributor to the overall volume of the power system. Several options are available to select from including gas storage tankage, cryogenic flasks, metal hydrides and chemical storage. 3000 psi commercially available metal storage tanks represent the lowest cost and lowest technical risk option. The volume and weight penalties for this option however are moderate. 6000 psi reactant storage has been successfully demonstrated in many applications offering significant cost and weight savings at low technical risk. High pressure gas storage in composite tanks can offer

TABLE III

POWER SYSTEM OPTIONS

OPTION	MEMBRANE	CELL SIZE	# MODULES	MEETS DAPS POWER REQUIREMENT	TECHNICAL RISK
A	Nafion 120	0.78 Ft.^{2}	1	No	
B	Nafion 120	0.78 Ft.^{2}	2	No	
C	Nafion 120	1.23 Ft.^{2}	1	No	
D	Nafion 120	1.23 Ft.^{2}	2	Yes	Low/Medium
E	Nafion 117	0.78 Ft^2	1	No	
F	Nafion 117	0.78 Ft.^{2}	2	Yes	Low
G	Nafion 117	1.23 Ft.^{2}	1	Yes	Low/Medium
H	Nafion 117	1.23 Ft.^{2}	2	Yes	Low/Medium
I	Dow	0.78 Ft.^{2}	1	Yes	Medium
J	Dow	0.78 Ft.^{2}	2	Yes	Medium
K	Dow	1.23 Ft.^{2}	1	Yes	Moderate
L	Dow	1.23 Ft.^{2}	2	Yes	Moderate

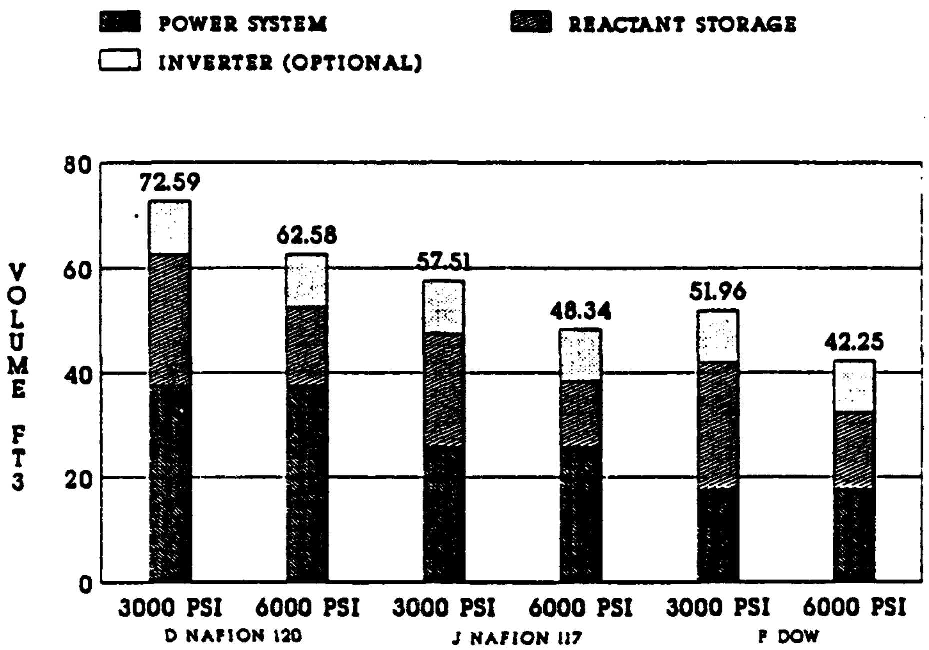
significant weight and volume savings at an increased cost and level of technical risk. Metal hydrides have been used in cases where volume is a critical consideration. This is often a slightly higher weight and higher technical risk means of storing hydrogen. Storage of reactants in cryogenic flasks often does not offer much in the way of volume advantage at a high technical risk and cost; especially when recharge is considered. Storage of reactants in chemical form has been demonstrated in previous buoy applications. Although technical risk is low, moderate cost may be incurred on multiple recharge of the system. The method of reactant recharge may be dictated by the reactant storage method employed.

There are commercial inverters available which would enable the conversion of D.C. power produced by the fuel cell to A.C. power. The size of these inverters may be reduced significantly by designing one to operate specifically for this application. In this case the heat rejection load would be significantly reduced since the inverter would only be required to operate a few seconds out of every hour. A promising option is to adapt existing fuel cell technology to produce alternating current directly thereby eliminating the need for an inverter. This mode of operation has already been successfully demonstrated in the laboratory.

It is expected that the DAPS fuel cell will weigh approximately 4500 pounds and will have a system volume of approximately 48 $Ft.^3$ including reactants. This system will cost approximately \$1700K per unit on a production basis. These numbers reflect a compromise between optimum weight, optimum volume, cost and technical risk for the assumed 400v/1000 amp requirement. For the 100 kW requirement, the power system would only weigh 3200 pounds and be contained within a volume of 29 $Ft.^3$. A system such as this would only cost \$700-800K per unit. With improved definition of system requirements, more specific information regarding system sizing and configuration may be provided.

Specific examples of several power system options are shown in Figure 33. Here, three membrane options are presented, each with two different reactant storage schemes. 3000 psi and 6000 psi gas storage options were chosen due to

DAPS POWER SYSTEM VOLUME



DAPS POWER SYSTEM WEIGHT

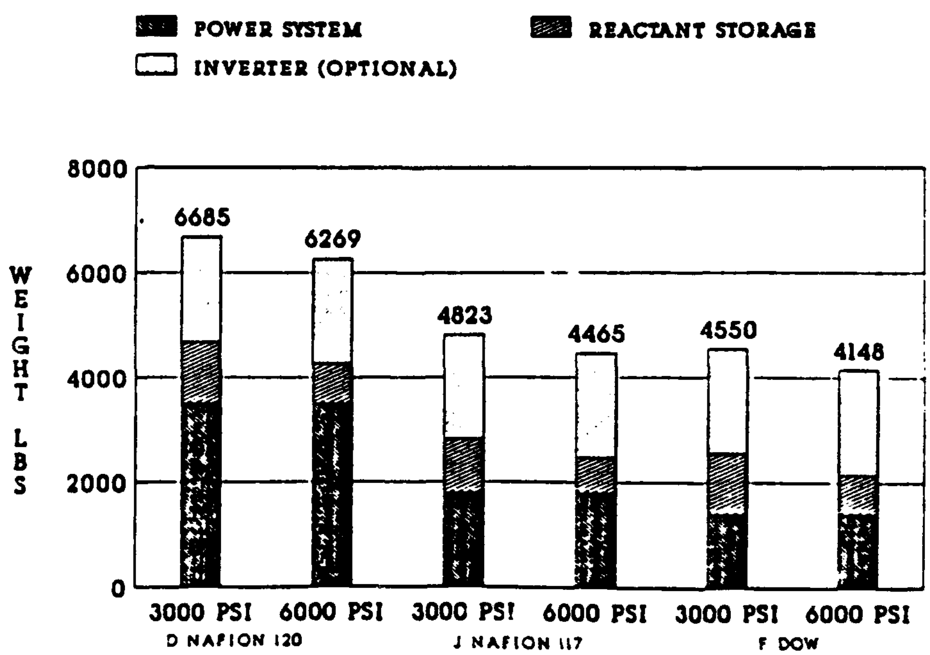


FIGURE 33. Representative Fuel Cell Power Systems

the low technical risk of implementation and ease of recharge. Of the three membrane options, Nafion 120 represents the lowest technical risk option while the Dow membrane represents the highest. A higher performance membrane option, Nafion 117 offers significant weight and volume savings over the Nafion 120 at slightly increased technical risk, thereby providing an equitable compromise. The system volumes and weights presented here may be very significantly reduced if either the nominal power output of 100 kW is maintained, or if the assumed output voltage (400 V) is reduced.

APPENDIX

APPENDIX - CUMULATIVE EXPERIENCE

The extensive experience that Hamilton Standard has in developing and manufacturing fuel cells and equipment for Naval applications makes it possible for a seaworthy power system having the following features to be produced:

Safety - Over the past thirty years, Hamilton Standard has refined the approach to provide "man-rated" system safety into SPE electrochemical cells. This approach has been verified in the Gemini, Biosatellite and Space Shuttle Technology fuel cell programs, along with the oxygen generating plant that is presently being used by the U.S. Navy.

Reliability - The low failure rate of the hydrogen/oxygen fuel cell components has been determined from 5.5 million hours of fuel cell testing. From these tests, a failure rate of 0.36×10^{-6} failures/hour for individual cells was established. System components were selected, based on the extensive experience at Hamilton Standard with fuel cells and undersea systems.

Simplicity - The SPE hydrogen/oxygen fuel cell is a "self-regulating" device in which reactants are consumed on demand in proportion to the load. Few components are necessary to support system operation, therefore promoting low cost and high reliability.

Maintainability - The power system is designed to meet the anticipated mission duration with no service requirement. Only reactant charging and product water removal are necessary prior to deployment and after return to the Mother vehicle. In the unlikely event that the service of one or more of the power system components is necessary, the power system is designed such that components are readily accessible and easily replaced.

Efficiency - The SPE fuel cell and associated system can be easily packaged such that high energy densities are achievable. This is a direct result of the inherent high efficiency of the SPE fuel cell.

Certification - Acceptance and certification guidelines have been established in order to ensure proper power system operability and construction. These guidelines are similar to those used for acceptance and verification of the oxygen generating plant developed by Hamilton Standard for the U.S. Navy.

The following pages depict development history of technologies which contribute directly to the state-of-the-art fuel cell power system design.

DOE ET AL - BULK HYDROGEN GENERATION PROGRAM (1975-PRESENT)

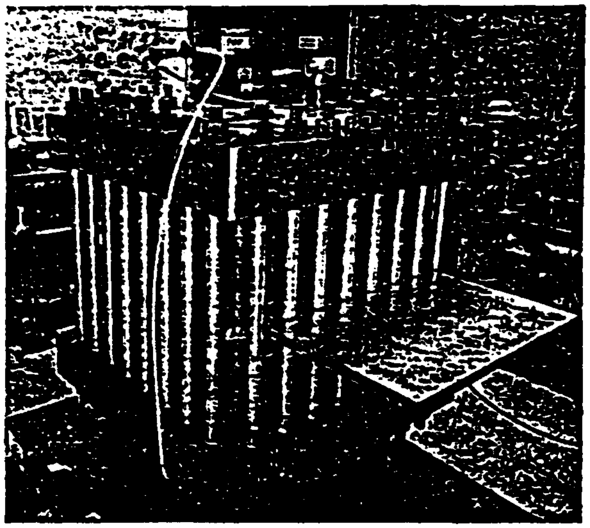
SCOPE: DEVELOP ELECTROLYSIS TECHNOLOGY WITH GOAL OF 85-90% EFFICIENCY, $250/KW CAPITAL COST

DESIGN FEATURES

- LOW COST MOLDED GRAPHITE CELL HARDWARE, GASKETLESS SEALS
- PNEUMATIC END PLATE LOADING
- 2-1/2 FT^2 AND 10 FT^2 CELL AREAS
- LOW COST ELECTRODES
- 3000 MA/CM^2 MAXIMUM CURRENT DENSITY
- 115°C COOLANT TEMPERATURE

ACCOMPLISHMENTS

- CATALYST LOADING OF 0.25 MG/CM^2 DEMONSTRATED
- $>$5000 HOURS AT 150°C DEMONSTRATED TO DATE
- $>$70,000 HOURS AT 80°C DEMONSTRATED TO DATE
- TEN CELL MODULE (1 FT^2 CELLS) ACCUMULATED $>$6000 HRS AT 2000 ASF

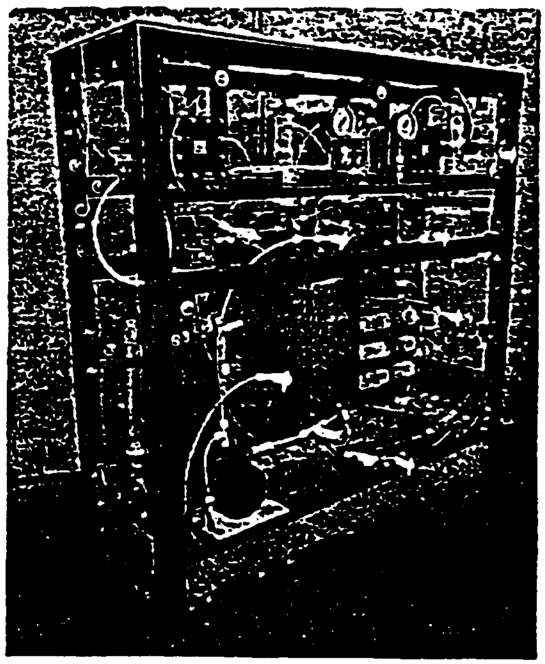


USAF BMO - HYDROGEN/BROMINE REGENERATIVE FUEL CELL PROGRAM (1976-PRESENT)

SCOPE: DEMONSTRATE FEASIBILITY OF $>$80% ENERGY STORAGE EFFICIENCY

DESIGN FEATURES:

- LOW COST HBR/BR_2 ELECTRODE
- 74% ELECTRIC TO ELECTRIC EFFICIENCY DEMONSTRATED @ 300 ASF, $>$90% @ 100 ASF
- DEMONSTRATOR SUCCESSFULLY OPERATED FOR APPROXIMATELY 4000 HOURS BY CUSTOMER



NASA - RLSE ELECTROLYSIS PROGRAM (1975-1978)

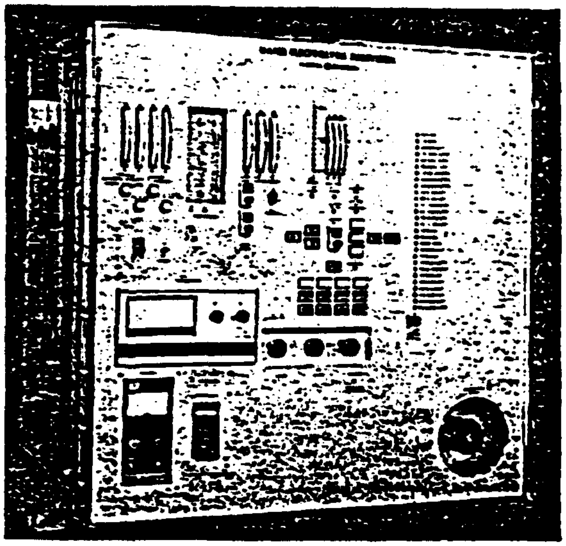
SCOPE: DEVELOPMENT AND FABRICATION OF THREE-MAN PRE-PROTOTYPE ELECTROLYSIS UNIT FOR NASA'S REGENERATIVE LIFE SUPPORT EVALUATION PROGRAM

DESIGN FEATURES

- PRESSURE HOUSING FOR 400 PSIA GAS GENERATION
- MICROPROCESSOR CONTROL FOR COMPLETELY AUTOMATIC OPERATION
- PROVISION FOR REMOTE DATA ACQUISITION
- 350 MA/CM^2 MAXIMUM CURRENT DENSITY
- 80°C COOLANT TEMPERATURE

ACCOMPLISHMENTS

- $>$ 900 HOURS OF AUTOMATIC, UNATTENDED OPERATION DEMONSTRATED PRIOR TO DELIVERY IN 1978
- $>$ 2900 HOURS ACCUMULATED ON TEST AT NASA/JSC TO DATE



USN - SUBMARINE OXYGEN GENERATION PLANT (1975-PRESENT)

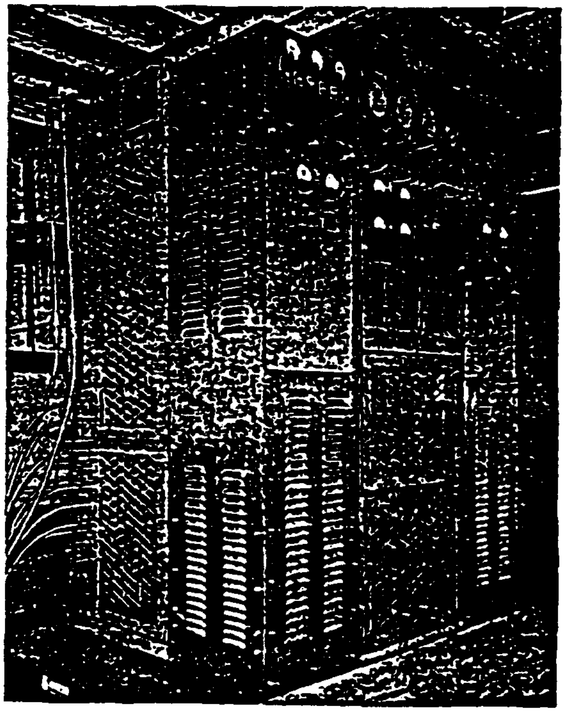
SCOPE: DEVELOPMENT OF A HIGH PRESSURE OXYGEN GENERATING PLANT (OGP) TO PROVIDE ON-BOARD ENVIRONMENTAL OXYGEN FOR NUCLEAR SUBMARINE CREWS

DESIGN FEATURES

- ELECTROLYSIS MODULE DESIGNED FOR 3000 PSIA
- PREPROTOTYPE SYSTEM DESIGNED FOR FULLY AUTOMATIC CONTROL WITH MICROPROCESSOR
- CELL SEAL DESIGN FOR 750 PSI DIFFERENTIAL PRESSURE
- 1500 MA/CM^2 MAXIMUM CURRENT DENSITY
- 50°C COOLANT TEMPERATURE

ACCOMPLISHMENTS

- DEMONSTRATED PREPROTOTYPE SYSTEM OPERATION AT PRESSURES UP TO 300 TO 3000 PSIA FOR 14,500 HOURS
- $>$ 10,000 HOURS LIFE TESTING COMPLETED ON EACH OF TWO 100-CELL ELECTROLYSIS MODULES TO DATE
- LIFE TESTED SINGLE CELLS UP TO 70,000 HOURS TO DATE
- TOTAL PROGRAM CELL LIFE TEST HOURS TO DATE - $>$ 3 MILLION
- DEMONSTRATED PROTOTYPE SYSTEM OPERATION FOR $>$ 10,000 HOURS TO DATE WITH $>$ 2500 HOURS AT 3000 PSIA



USN - HASPA FUEL CELL PROGRAM (1976-1977)

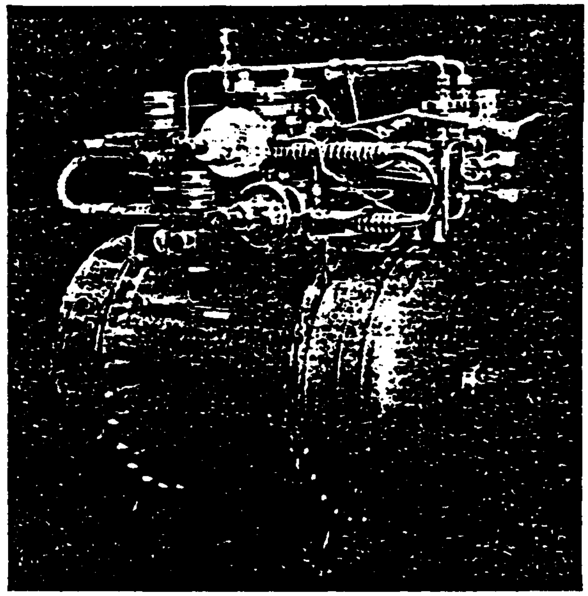
SCOPE: FABRICATE, TEST AND DELIVER COMPLETE 3 KW FUEL CELL SYSTEM AND GONDOLA FOR SEVEN-DAY MISSION OF HIGH ALTITUDE SUPER PRESSURED AEROSTAT (HASPA)

DESIGN FEATURES

- USED 32 CELL STACK FROM SPACE SHUTTLE TECHNOLOGY PROGRAM
- COMPLETE AUTOMATED SYSTEM DESIGN FOR UNMANNED MISSION
- 230 MA/CM^2 MAXIMUM CURRENT DENSITY
- 80°C COOLANT INLET TEMPERATURE

ACCOMPLISHMENTS

- FUEL CELL STACK DEMONSTRATED NO LOSS IN PERFORMANCE FOLLOWING 1000 HOURS TESTING UNDER SHUTTLE PROGRAM, TWO YEARS INACTIVE STORAGE AND ADDITIONAL 1000 HOURS TESTING IN HASPA PROGRAM



NASA - ADVANCED FUEL CELL TECHNOLOGY PROGRAM (1974-PRESENT)

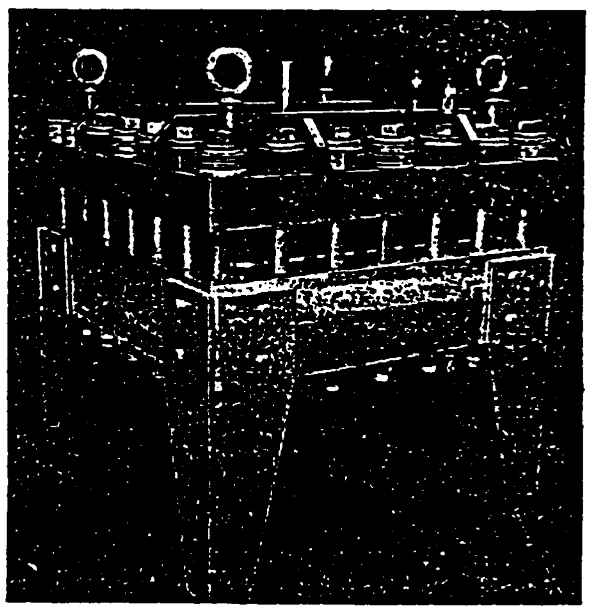
SCOPE: CONTINUING DEVELOPMENT OF SOLID POLYMER ELECTROLYTE FUEL CELL TECHNOLOGY TO ACHIEVE IMPROVED PERFORMANCE, SMALLER SIZE, LIGHTER WEIGHT AND REDUCED COST; DEMONSTRATE IMPROVEMENTS IN MULTI KW MODULE

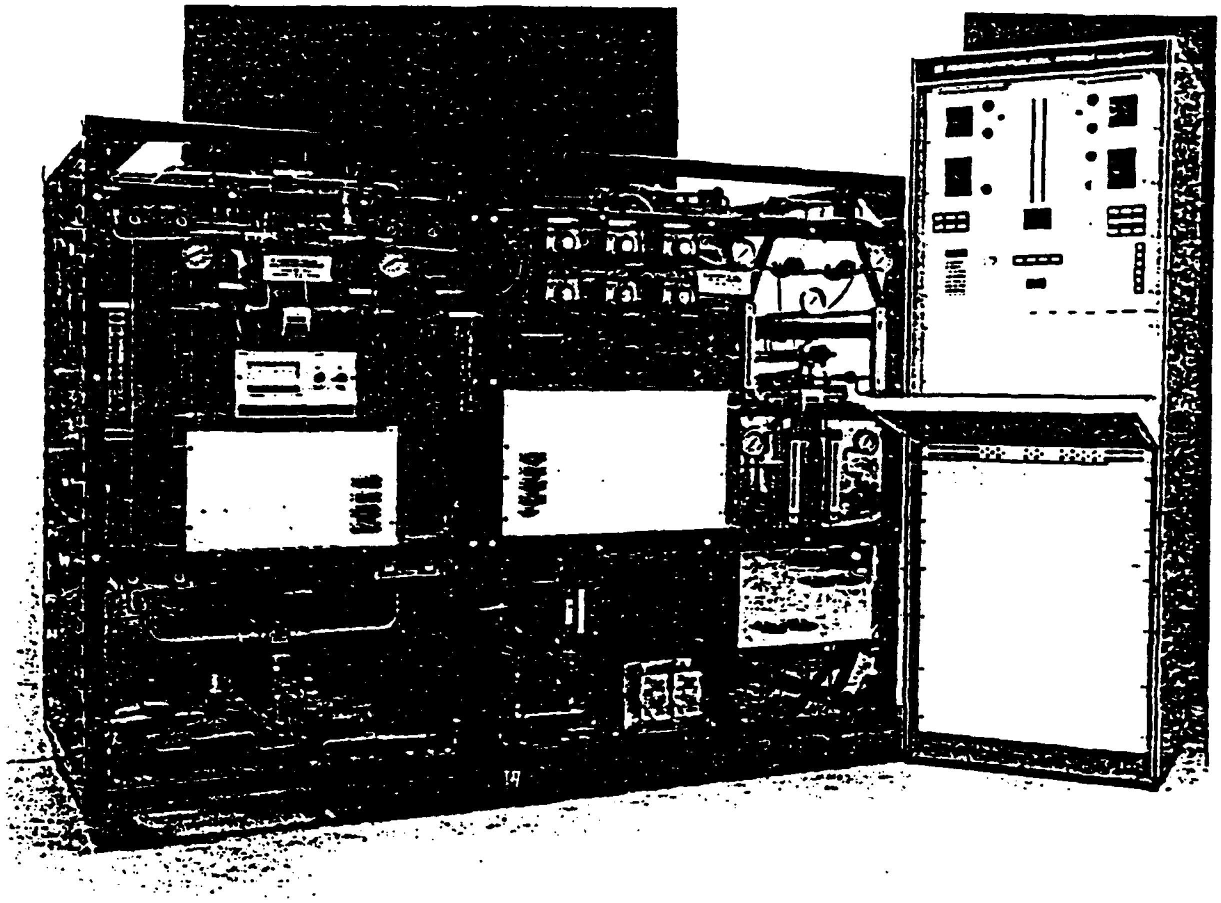
DESIGN FEATURES

- HIGH CURRENT DENSITY, BI-POLAR DESIGN
- ELIMINATION OF WATER COLLECTION WICKS
- ELIMINATION OF BONDED AND GASKET SEALS
- 5 MIL ELECTROLYTE SHEET
- 500 MA/CM^2 DESIGN CURRENT DENSITY
- 80°C COOLANT INLET TEMPERATURE

ACCOMPLISHMENTS

- DEMONSTRATED PERFORMANCE UP TO 1300 MA/CM^2 AT 0.7 V
- SIGNIFICANT COST REDUCTION FROM SPACE SHUTTLE DESIGN
- DEMONSTRATED OPERATION ON CONTAMINATED REACTANTS
- SCALE UP TO 1.1 FT^2 CELL AREA
- 3000+ HR TEST COMPLETED WITHOUT PERFORMANCE DEGRADATION
- 4 KW STACK COMPLETED 2000 HOURS OF VERIFICATION TESTING WITH INVARIENT PERFORMANCE





NASA - LOW EARTH ORBIT ENERGY STORAGE (REGENERATIVE FUEL CELL) (1979-PRESENT)

SCOPE: • TO DEVELOP THE TECHNOLOGY TO PROVIDE ELECTRICAL ENERGY STORAGE FOR LARGE LOW EARTH ORBIT SPACECRAFT BY THE LATE 1980'S. SYSTEMS WOULD BE IN THE 50+ KW RANGE.

DESIGN FEATURES:

- COMBINED USE OF PREVIOUSLY DEVELOPED FUEL CELL AND ELECTROLYZER TECHNOLOGIES
- HIGH ENERGY STORAGE EFFICIENCY
- INTEGRATION WITH PROPULSION SYSTEMS AND ENVIRONMENTAL CONTROL SYSTEMS

ACCOMPLISHMENTS

- LABORATORY BENCH-TYPE REGENERATIVE SYSTEM COMPLETED:
  - ~1600 OPEN-LOOP ORBITAL CYCLES
  - ~ 350 CLOSED-LOOP ORBITAL CYCLES
- DELIVERABLE BREADBOARD HAS BEEN OPERATING AT NASA/JSC SINCE MID 1983 HAVING ACCUMULATED OVER 1500 SIMULATED 90-MINUTE ORBITS TO DATE

USN/USAF - AIRCRAFT OXYGEN GENERATOR PROGRAM (1972-1976)

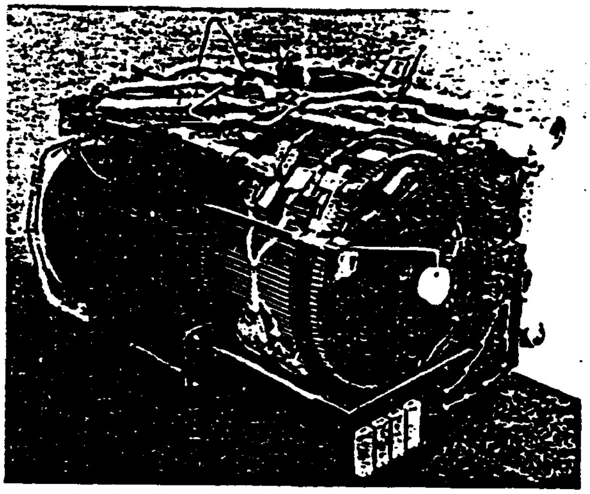
SCOPE: DEVELOPMENT, FABRICATION AND DELIVERY OF PROTOTYPE 2-MAN, OPEN LOOP OXYGEN GENERATION SYSTEM FOR FIGHTER AIRCRAFT

DESIGN FEATURES

- AIR DEPOLARIZED ELECTROLYSIS CELLS
- 120-CELL STACK, 55 IN^2 CELLS, GASKETLESS SEALING
- 400 PSIA OPERATION WITHOUT PRESSURE HOUSING
- PNEUMATIC END-PLATE LOADING
- 270 MA/CM^2 MAXIMUM CURRENT DENSITY
- 82°C OPERATING TEMPERATURE MAXIMUM

ACCOMPLISHMENTS

- SUCCESSFULLY DEMONSTRATED GASKETLESS SEALING AND FLIGHT WEIGHT PNEUMATIC END PLATES FOR HIGH PRESSURE
- ACHIEVED LIGHT WEIGHT (~102 LB), LOW VOLUME (~2 FT^3) FOR FLIGHT SYSTEM REPRESENTATIVE OF > 11 KW ELECTROLYZER



NASA - SPACE SHUTTLE FUEL CELL TECHNOLOGY PROGRAM (1970-1974)

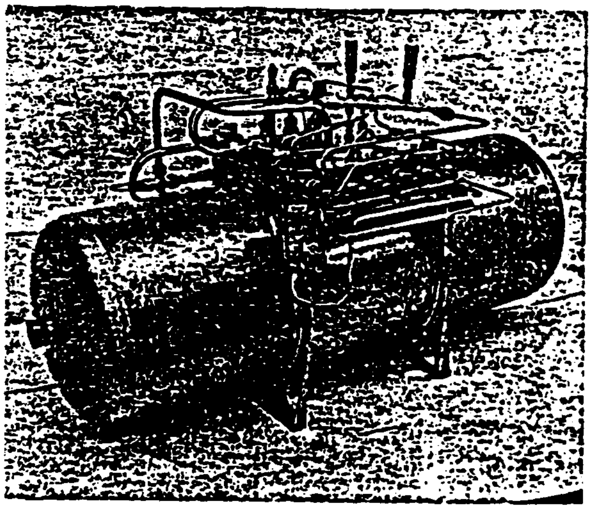
SCOPE: DEVELOP AND DEMONSTRATE SUITABLE FUEL CELL MODULE DESIGN TO MEET ANTICIPATED SPACE SHUTTLE REQUIREMENTS

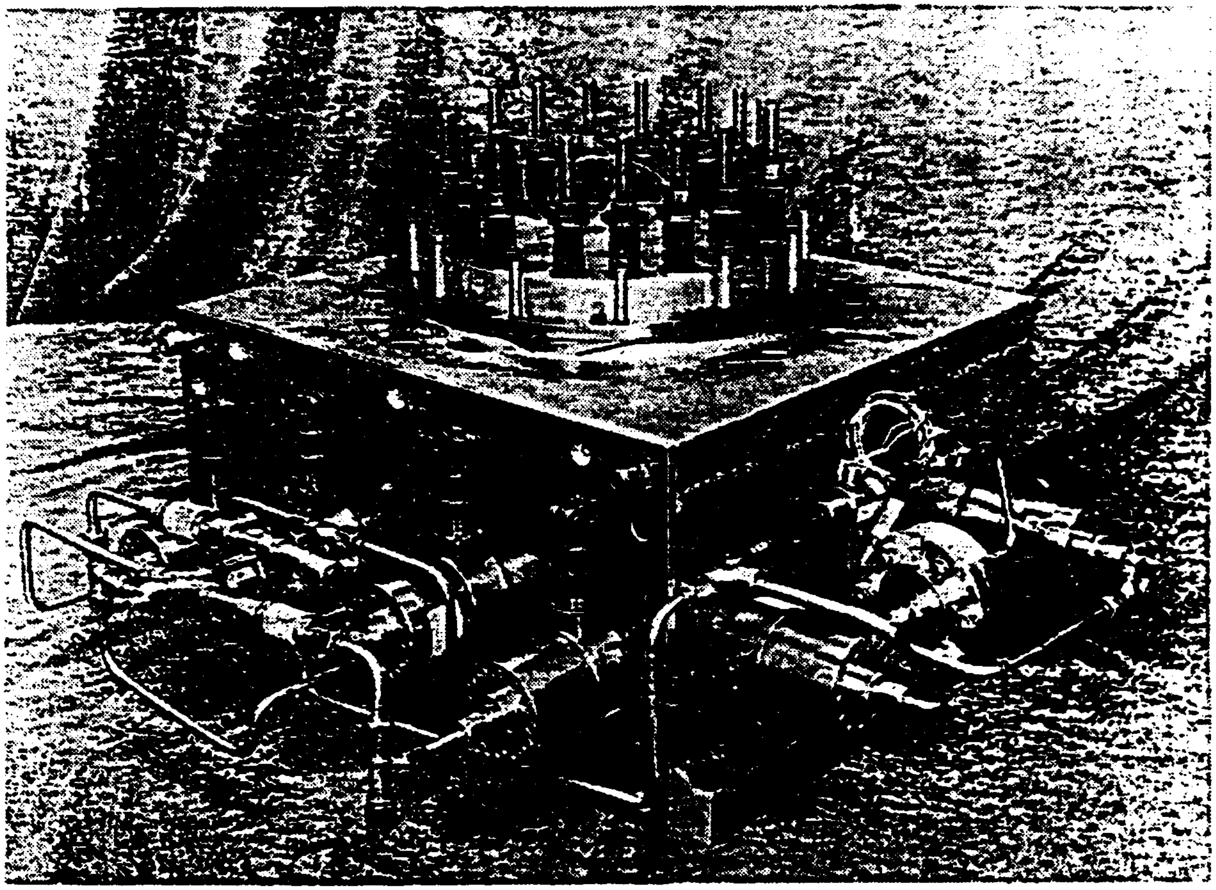
DESIGN FEATURES

- BACK-TO-BACK CELL DESIGN (EDGE CURRENT COLLECTION)
- INTERNAL REACTANT PRE-HUMIDIFIER
- 185 MA/CM^2 MAXIMUM CURRENT DENSITY
- 80°C COOLANT INLET TEMPERATURE

ACCOMPLISHMENTS

- 5 KW MODULE COMPLETED, INCORPORATING TWO 2-1/2 KW STACKS
- 5000 HOUR LIFE TEST SUCCESSFULLY COMPLETED ON 38-CELL STACK
- 2000 HOUR LIFE TEST SUCCESSFULLY COMPLETED ON 2-1/2 KW MODULE
- DEMONSTRATED IMPROVED PERFORMANCE, HIGHER TEMPERATURE OPERATION





THE MARQUARDT COMPANY/USAF - ELECTROLYSIS SYSTEM FOR SATELLITE PROPULSION (1981-1983)

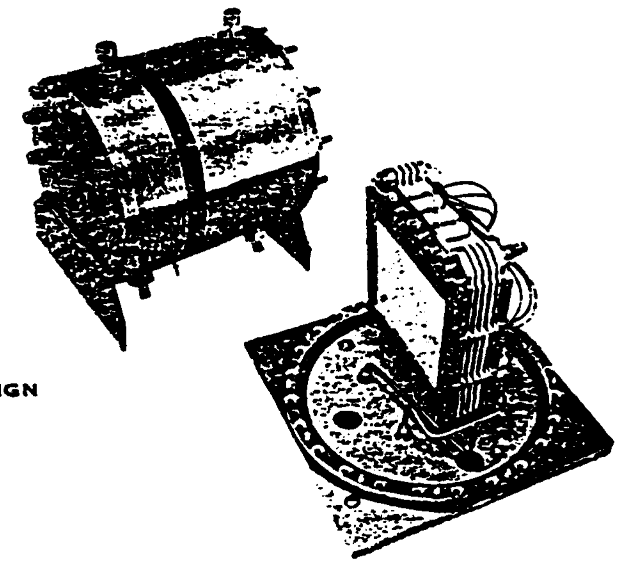
SCOPE: DEVELOP, FABRICATE AND DELIVER A FLIGHT WEIGHT FULL SIZED HIGH PRESSURE ELECTROLYZER FOR SATELLITE PROPULSION

DESIGN FEATURES

- STATIC VAPOR FEED
- CONDUCTIVE COOLING
- PRESSURE DOME ELIMINATED
- 800 PSI (NON-OPERATIONAL)
- 400 PSI (OPERATIONAL)

ACCOMPLISHMENTS

- DEMONSTRATED 800 PSI CAPABILITY ON 2 NON-OPERATING UNITS FOR OVER 5 YEARS
- DEMONSTRATED LEAKAGE RATE OF LESS THAN 1 POUND WATER LOSS IN 10 YEARS
- OPERATED FULL MODULE FOR > 1300 HOURS PRIOR TO DELIVERY TO CUSTOMER (I.E., THE MARQUARDT COMPANY)
- OPERATED SYSTEM FOR > 2500 HOURS AT CUSTOMER FACILITY



AIR FORCE - REGENERATIVE FUEL CELL PROGRAM (1968-1970, 1972-1973)

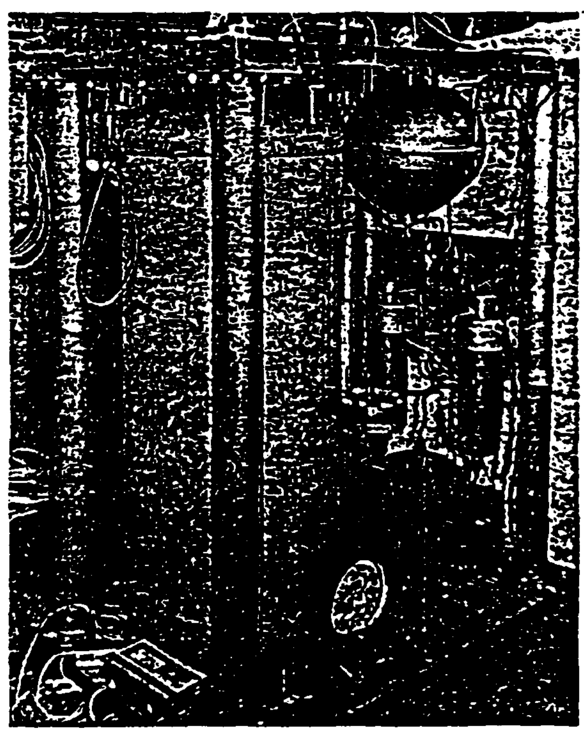
SCOPE: EXPLORATORY DEVELOPMENT AND FEASIBILITY TESTING OF REGENERATIVE FUEL CELL SYSTEMS USING BOTH DEDICATED ELECTROLYSIS/FUEL CELL MODULES AND REVERSIBLE SINGLE CELL MODULES.

DESIGN FEATURES

- STANDARD FUEL CELL AND ELECTROLYSIS CATALYSTS
- STATIC, CAPILLARY WATER TRANSPORT
- LABORATORY/BREADBOARD HARDWARE DESIGN

ACCOMPLISHMENTS

- FEASIBILITY DEMONSTRATED
- PRELIMINARY DESIGN STUDY COMPLETED



THE MARQUARDT COMPANY/USAF-ELECTROLYSIS SYSTEM FOR SATELLITE PROPULSION (1971-1975)

SCOPE: DEVELOP, FABRICATE AND DELIVER AN ENGINEERING MODEL:HIGH PRESSURE ELECTROLYZER FOR SATELLITE PROPULSION

DESIGN FEATURES

- HIGH PRESSURE DESIGN FOR 500 PSI
- STATIC VAPOR FEED
- CONDUCTIVE COOLING

ACCOMPLISHMENTS

- DEMONSTRATED HIGH PRESSURE, STATIC VAPOR FEED DESIGN WITH 82% ELECTROLYSIS EFFICIENCY
- SUCCESSFULLY COMPLETED > 4000 HOURS IN COMPLETE THRUSTOR SYSTEM TEST AT MARQUARDT

MERDC - ARMY FUEL CELL PROGRAM (1966-1968)

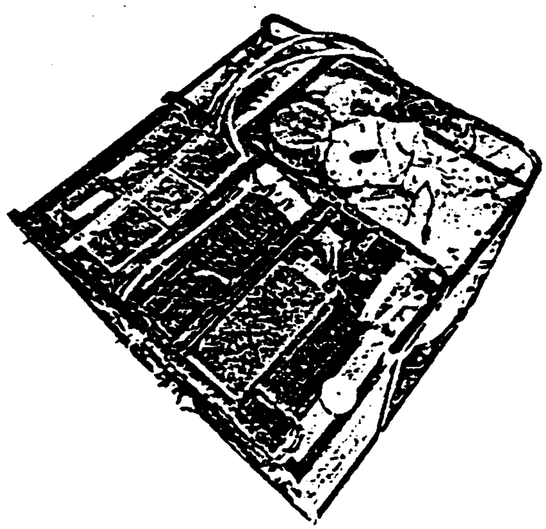
SCOPE: DEVELOPMENT, FABRICATION AND DELIVERY OF A 1.5 KW FUEL CELL POWER PLANT OPERATING ON JP-4.

DESIGN FEATURES:

- 2 KW SPE STACK (58 CELLS)
- REFORMER/SHIFT FUEL PROCESSOR
- WATER CONSERVATIVE
- 150 POUND WEIGHT, INCLUDING FUEL
- 8 CUBIC FEET VOLUME

ACCOMPLISHMENTS

- SUCCESSFULLY DEMONSTRATED COMPLETE SOLID POLYMER ELECTROLYTE POWER PLANT FUELED WITH JP-4.
- SYSTEM DELIVERED TO MERDC FOLLOWING DEMONSTRATIONS AT THE FACTORY



MDAC/NASA - GEMINI FUEL CELL PROGRAM (1962-1966)

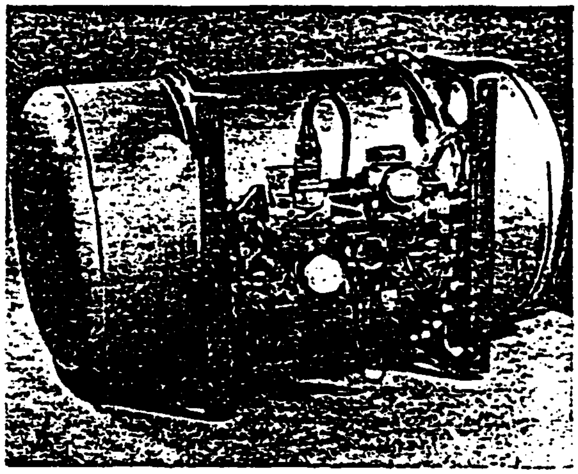
SCOPE: DEVELOPMENT AND PRODUCTION OF FUEL CELLS FOR THE GEMINI SPACECRAFT PROGRAM.

DESIGN FEATURES

- THREE 32-CELL STACKS IN EACH OF TWO 1 KW MODULES.
- PASSIVE SEPARATION OF PRODUCT WATER IN ZERO G.
- HIGH SYSTEM RELIABILITY THROUGH STACK AND COOLANT SYSTEM REDUNDANCY.
- POLYSTYRENE SULFONIC ACID USED AS ELECTROLYTE.
- 45 MA/CM^2 MAXIMUM CURRENT DENSITY.
- 23°C COOLANT INLET TEMPERATURE

ACCOMPLISHMENTS

- 7 SUCCESSFUL MANNED SPACE FLIGHTS.
- 250, 32-CELL STACKS PRODUCED.
- 850 HOURS (5000 STACK HOURS) OF FLIGHT OPERATION.
- 80,000 STACK-HOURS OF OPERATION.



GE/NASA - BIOSATELLITE FUEL CELL PROGRAM (1964-1968)

SCOPE: DEVELOP 360 WATT FUEL CELL FOR USE ON 30-DAY MISSIONS OF BIOSATELLITE SPACECRAFT.

DESIGN FEATURES

- SINGLE 32-CELL STACK.
- FIRST OPERATIONAL USE OF NAFION® SOLID POLYMER ELECTROLYTE MATERIAL.
- IMPROVED VERSION OF GEMINI FUEL CELL DESIGN.
- 45 MA/CM^2 MAXIMUM CURRENT DENSITY.
- 38°C COOLANT INLET TEMPERATURE.

ACCOMPLISHMENTS

- SUCCESSFUL OPERATION FOR 40 DAYS IN ORBIT.
- 8,000 HOUR LIFE DEMONSTRATED.
- DEMONSTRATED SUCCESSFUL OPERATION WITHOUT H_2 PURGING.

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